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SOIL SCIENCE

BY

WILBERT WALTER WEIR

SOIL SCIENCE

Its Principles and Practice

REVISED EDITION

by

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PREFACE—SECOND EDITION

In this book the author's aim is to set forth a body of knowledge that may be called *soil science,* adapted for undergraduate use in agricultural colleges and technical schools and also for use by anyone interested in farming, forestry, gardening, and in growing greenhouse and potted plants.

In determining what subjects soil science should embrace, the author considered carefully all the many subjects discussed by members of the International Society of Soil Science. Further, according to the definitions of *soil,* soil science should also include a discussion of the function of soils in relation to growing plants.

Soil science, like other natural sciences, is systematized knowledge, embracing theories, facts, generalizations, and principles. Thus, *soil science is systematized knowledge of soils and soil fertility, with a view to an understanding of the nature of soils themselves, their relation to each other, and their role in plant nutrition and crop production.*

The author has recognized the need for fundamental facts about soils, soil fertility, and soil conservation in general, and for basic principles regarding soils. With such basic knowledge one can understand better not only local or specific soil conditions but also the relation of local soil conditions to the principles and practice of soil science, which are important. For the first college course in soils, the author believes that the students should gain a general view of soil science, for which purpose this book has been designed.

The plan of *Soil Science* may be briefly described as follows: The introductory chapter treats of the evolution of agriculture in relation to the development of scientific thought. It is a singular fact that the development of scientific thought intertwined with the development of agriculture. When primitive peoples began to till the ground for food plants, they initiated a decided advance in projecting their minds into the realm of natural phenomena. The ancients in their philosophies devoted considerable attention to the tillage and culture of food crops. Modern agriculture was established on a scientific basis when Liebig (Ger., 1840) inferred that

green plants absorbed simple substances like water and mineral matter from soils, and also ammonia and carbon dioxide, and with the aid of sunlight converted them into complex organic compounds.

Then follow four chapters that call attention to the fact that soils, which seem to be simple bodies, are, in fact, very complex—with interacting physical, chemical, and biological properties. These four chapters also show the relation of certain inherent qualities of soils and basic facts about them to plant growth and crop production.

It would be amiss if early in this book nothing were said about scientific classification of soils and the basic principles of such a classification. It seems highly desirable, therefore, that chapters 2, 3, 4, and 5 be followed by general information about soil genesis and those distinguishing characteristics that warrant the consideration of soils as objects of natural science. Such information should not only enlarge one's concept of soils but also emphasize the fact that the noting of similarity in soils and the discovery of soil features that make possible scientific classes are among the first steps in soil science.[1] Moreover, early in his study of soil science, one should become familiar with the scientific names of soil classes, especially of soil types, because references to soils by scientific classes are common in modern agricultural literature. Hence chapters 6, 7, and 8, are entitled "The Modern Concept of Soils," "Soil Classification," and "Natural Order in Soils."

Chapters 9 and 10, entitled "Soil and Plant Relationships" and "Crop Production and Soil Fertility," are designed to show the relation between soils and plant growth. In the broad sense, this relationship expresses itself in crop production, commonly called *soil fertility* or *soil productivity*.

Then follow chapters 11 to 24, in which are discussed the various factors of soil fertility, namely, tilth and tillage, soil water, soil aëration, soil reaction, soil organic matter, soil micro-organisms, plant nutrient elements, and crop rotation.

Soil Science can hardly be called complete without a discussion of soil conservation, an important field of human endeavor in which are afforded wide opportunities for the application of soil science. In chapter 25 on soil conservation, the two principal divisions are "Soil Erosion" and "Watershed Protection."

[1] See CLASSIFICATION, by Abraham Wolf, in the Encyclopedia Britannica, Vol. 5, 14th edition, 1929. New York.

The last two chapters of this book are supplementary. They discuss briefly some of the ways in which the need for fertilizers may be determined and some points that may be considered in the interpretation of results obtained in fertilizer experiments.

The working out of *Soil Science* proved to be almost a lifetime project. First thoughts were given to it when the author was a junior in the University of Wisconsin; but actual work was not done until later, when he became a teacher and soil investigator at that institution. From year to year new fields of inquiry in soil science opened, new discoveries made, and new experiences gained, until the objects to be attained became clearer and assumed greater importance.

The author found it necessary to study soils and agriculture in every State and parts of Canada and Mexico. In addition to farming, teaching, extension, research, and editorial experiences, he has had exceptionally wide commercial opportunities to evaluate farm lands and to study soil improvement through the use of commercial fertilizers. Thus he has studied not only the scientific and practical aspects of soil science on a wide basis, but has also tested certain current theories of soil fertility, and has put to practical test various theories of soil classification. For several years since 1934 the author has been in the arid-semiarid mountainous region of southwestern United States, giving much attention to soils, run-off, soil erosion on the watersheds, and to the planning of remedial programs for soil and water conservation and watershed protection, in aid of flood control.

The results of soil investigations (up to the very latest) are credited throughout this book. The names of the scientists concerned are given, and also the countries they represent and the years when they made their contributions. The author has drawn freely upon contributions made by fellow workers in soil science and by others in the related sciences, to whom he gratefully acknowledges his indebtedness.

WILBERT W. WEIR.

PREFACE

Possibly there is no subject that lies closer to the welfare of the human race, with its population of nineteen hundred millions of people, than the production and maintenance of the necessary food supply; and it is particularly gratifying to know that today soil science has so far advanced that one may confidently assert that, in the absence of some catastrophe of nature or a war of extinction, mankind need never fear starvation or the want of food. Such an eventuality has been made unlikely by scientific methods of agriculture, increased knowledge of the soils themselves, better understanding of plant growth, and improved methods for taking care of and preserving the soils.

In the following chapters the reader will find a discussion of the development of agriculture from the time primitive people first cultivated the ground for food crops to the present time, and full treatment of the nature of soils—physical, chemical, and biological—of the fundamentals of a scientific classification of soils, and of the vital relationship between soils and growing plants. There is also a study of the principal factors that determine soil productivity and a résumé of the progress made in the conservation of agricultural, range, and forest lands. The illustrations of the important soils of the world will be found of great assistance in the study of all phases of soil science.

The subjects treated, as listed in the Contents, are the same as those considered at the congresses of the International Society of Soil Science.

Although the scope of *Soil Science* is thus broad and comprehensive, the author has not lost sight of his desire to bring within the reach of college students studying agriculture, and all others who may be interested in soil cultivation, land conservation, and plant growth, the basic principles pertaining to soils and their fertility.

It is hoped that interest may be stimulated by examples that show application of these fundamentals in agricultural research,

farming, forestry, gardening, and in the growing of greenhouse and potted plants.

This book was really begun 25 years ago when the author, who was at that time connected with the University of Wisconsin as teacher and investigator, became interested in the principles of soil genesis and soil fertility. Not finding any authoritative or satisfactory theory in regard to soil science, he determined to make an extended study of the problems involved and to collect material for a comprehensive presentation of the subject.

Soil Science contains not only a systematic study of soils and their classification, but also of soil fertility and agricultural practices. The author has studied soils and agriculture in every State in the United States and in parts of Canada. In addition to farm-management, college-teaching, agricultural-extension, research, and editorial experience, the author also has had exceptional commercial opportunities to evaluate farm lands and to study the improvement of crop production through the use of fertilizers. Thus has he been able to study not only the scientific and practical aspects of soil science on a wide practical basis, but also to test certain current theories regarding soil fertility and to examine and study carefully various theories of soil classification.

As to the actual writing of these pages, the author spent his entire time for nearly two years in getting the immense mass of material he had accumulated ready for the printer in the form of this book, and it has been revised and re-revised up to the time of its publication. From year to year new fields of inquiry regarding soils and their fertility opened, new discoveries were made, and new experiences were acquired, until the object to be attained became clearer and assumed even greater importance.

The experimental findings of investigation (up to the very latest) are credited throughout the book. Thus there will be found authoritative data that bears on all phases of soil science. The names of the scientists are given, and also the countries they represent and the years when they made their contributions. Credit to American workers is indicated as "Hilgard (1906)," and to investigators other than those of the United States, as "Liebig (Ger., 1840)."

The author believes, with many teachers of agriculture, that students who are studying soils for the first time should gain a bird's-eye view of soil science.

The author gratefully acknowledges his indebtedness to fellow

workers in soil science and others, particularly to the following: Dr. M. S. Anderson, Bureau of Chemistry and Soils, United States Department of Agriculture, for suggestions regarding soil colloids; J. F. Breazeale, research biochemist, University of Arizona, Tucson, Ariz., for careful reading of the chapters that deal with soil chemistry, biochemistry, and soil-and-plant relations; Dr. F. W. Parker, Wilmington, Del., for constructive criticism regarding fertilizers and their effects on soils; Dr. Frank W. Collier, American University, Washington, D. C., for helpful suggestions regarding the laws of thought and their application in soil science; and especially to Mr. R. A. Webster, Tucson, Ariz., for his most helpful assistance in the final preparation of the manuscript.

If something has been added to our knowledge of the great science that is the basis of all our efforts to perpetuate existence and make life happier and mankind more content with his lot, all the efforts of the author will be repaid many fold.

Students should use the Index in consulting other chapters for topics that are related to those in hand.

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CONTENTS

SOIL SCIENCE

CHAPTER 1

DEVELOPMENT OF AGRICULTURE AND RISE OF SCIENTIFIC THOUGHT

Archeological research indicates that cultivation of soils for the production of food crops began during the neolithic stage of human culture, about 10,000 years ago, and that primitive people initiated a decided advance in civilization by greatly enlarging their powers over nature.[1] (See Preface.)

This primitive agriculture seems to mark the transition from the lowest stage of human culture—from savagery and nomadic forms of life—to settled existence. The new art of cultivating the ground, together with domestication of animals, enabled our early ancestors to lead a much less precarious existence, and the provision of certain high-yielding crops gave them greater opportunity for the development of the better things of life. Thereafter, civilization became a social process in which there was afforded the opportunity for thinking individuals, slowly it is true, to advance culture greatly through the exercise of their mental powers. In order to gain a better understanding not only of agriculture, but also of science itself, we shall endeavor to trace briefly these developments of human thought and experience in connection with soils.

Neolithic crops and tools. Apparently the first grains cultivated were barley, emmer, wheat, and millet. Neolithic people also used apples, pears, grapes, walnuts, raspberries, blackberries, parsnips, and pigweeds for food. Probably most of these plants grew wild at first; but with cultivation and selection, they gradually developed into more productive crops. Even at this early date flax was grown and used for making cloth and fishing nets. During the Neolithic age primitive races, in addition, learned the use of tools of flint, polished stone, and of wood, including simple digging sticks and hand mills.

Agriculture through historical periods. A study of the development of scientific thought in connection with agriculture will

[1] Recent findings in Palestine seem to show that agricultural pursuits were followed by the Natufians in Palestine and the Near East 20,000 years ago.

take us through the historical periods of ancient, medieval, and modern times. Agriculture began about 8000 B.C. and continued for about 6,000 years before any improvements over primitive methods were made. Gradually new ways of doing things were introduced into husbandry, and the earth yielded more "abundant fruit"; but about 500 years before the close of the ancient period improvements were arrested, owing to the decline of the ancient civilization. Following this comes the medieval period, from the fall of Rome in 476 until the discovery of America in 1492, when the modern era set in with a revival of the spirit of adventure and a general contest among the nations for discovery and conquest of new worlds.

ANCIENT HUSBANDRY

Obviously, the simplest methods predominated during thousands of years of ancient husbandry. Mankind was groping for a way to project the human mind into the realm of the unknown in search for truth regarding natural phenomena. Improvement was exceedingly slow, owing to lack of experience and knowledge, together with a superstitious belief that human woes resulted from a departure from the ancient standards. Each generation accepted existing conditions and the masses made no powerful concerted effort for betterment. The slow progress made by the neolithic people is not to be attributed to the structure of their brains, for anthropologists are quite agreed that the human brain typical of modern times shows no change in physical structure when compared with that of the Cro-Magnon man. This really means that there is no indication of any definite brain development in 30,000 years. The neolithic people made slow progress because they had only a meager accumulation of civilization.

Primitive methods. The term "primitive," as it is used here, means *first* and *crude*. Primitive methods of husbandry are not to be regarded as relics of ancient times alone—they were common during the Middle Ages, and they are still practiced in various parts of the world. However, some of the first steps in husbandry in widely divergent parts of the globe were not only extensive, but also paved the way for scientific achievement.

Irrigation. The practice of using artificial streams to supply water for crops occupied a prominent place in primitive agriculture. The reason for this is plain. Archeological studies of the Gobi area in China, of Egypt, Sumeria, Akkadia, Babylon, Crete,

Phoenicia, Nineveh, and Carthage show that civilizations were born and nurtured mostly in countries of limited rainfall and which now have mean annual temperatures ranging from 78° to 67° F. GilFillan (1920) has traced the movement of civilizations and world leadership in relation to the mean temperatures of the countries concerned, and has pointed out that the path of world supremacy has been moving rather steadily from warm to cooler regions.

Quiggin (Eng., 1929) has pointed out that primitive irrigation may vary from the hollow trunks of tree ferns, which the Fijians laid down to conduct water to their taro beds, to the imposing engineering works of the primitive farmers of Peru or to the extensive aqueducts of ancient Ceylon. When water had to be raised, it was hand-ladled, hand-bucketed, or lifted by means of a water-wheel turned by animal or man power.

In southwestern United States, especially in Arizona, hundreds of miles of ancient irrigation ditches and laterals have been traced, built probably about the beginning of the Christian Era. In the Salt River Valley alone prehistoric people at one time probably had 100,000 acres under irrigation. Primitive peoples of the earliest civilizations gave much attention to irrigation.

Assartage. The system of agriculture commonly used by primitive peoples of tropical and semitropical countries is assartage, which consists in grubbing and burning trees and brush on new patches of forest land each year to make them arable. When the soils of planted lands become exhausted, the clearings are abandoned to the wild vegetation. Cook (1919) has called this "milpa" agriculture, a system that is well suited to the needs of people of limited development, because of the minimum labor and equipment required. In South America, for example, the Indians plant maize in holes a few feet apart among the half-burnt branches and blackened trunks; and when the crop comes up, they clear and stir the ground with hoes. There is no rotation of crops. The clearing of new patches every year may continue so long as there are virgin or "second-growth" lands worth clearing.

The fact that certain regions that have supported large populations in times past are now uncultivated indicates the probability of a primitive civilization destroying through soil exhaustion the very basis of its own existence.

Terrace cultivation. The value of terracing was an early discovery. In hilly and mountainous regions of limited and irregular rainfall, terracing and irrigation have gone hand in hand. This is best illustrated by the practices of the Arabs in Yemen, Arabia, where on seaward slopes, at elevations of from 4,000 to 7,000 feet, the land is terraced, and the crops (coffee, tamarind, and fig) are irrigated from reservoirs which collect water during two rainy seasons each year. It is said that the husbandry here had its beginning in the sixth century after Christ.

In the mountain regions of India, Ceylon, Tibet, and China, where progress has been arrested, terrace cultivation is extensive. The Spanish conquerors found in Peru a high state of terrace husbandry, producing excellent crops of potatoes and maize. Archeology also shows evidence of terracing in the Mediterranean lands and in Britain 20 centuries before the Christian Era.

Primitive fertilizers. Fertilizing the ground was certainly known to the earliest primitive gardeners. By observing the effects of the droppings of their animals in open pastures, the first husbandmen learned very early the value of animal excrements for growing plants. Thus the use of all kinds of animal manures is probably as old as agriculture. This idea was applied in many ways. North American Indians used fish for fertilizing their corn, while those of South America used guano, excrement of sea birds. Wood ashes, compost, and waste wool are also to be counted among the early fertilizers.

The beneficial effects of chalk or marl in improving the ground for cropping were known to the Celts, a people who attained their greatest power in central and western parts of Europe about 500 B.C.

Reflecting on the problem of soil productivity as it affected early civilizations, Hilgard (1906) wrote:

> In humid countries, as is well known, cultivation can only in exceptional cases be continued profitably for many years without fertilization. But fertilization requires a somewhat protracted development of agriculture to be rationally and successfully applied in the humid regions. . . . No such need was felt by the inhabitants of the arid regions for centuries, for the native fertility of their soils, coupled with the fertilizing effects of irrigation water bringing plant-food from afar, relieved them of the need of continuous fertilization; while in the humid regions, the fertility of the land is currently carried into the sea by the drainage waters, through the streams and rivers, causing a chronic depletion which has to be made up

for by artificial and costly means. . . . The arid regions were, therefore, especially conducive to the establishment of the highly complex polities and high culture, of which the vestiges are now being unearthed in what we are in the habit of calling "deserts," the very sands of which usually need only the life-giving effects of water to transform them into fruitful fields and gardens.[2]

Primitive implements. The first implement used in agriculture was, undoubtedly, the digging stick. This is merely a strong wooden stick having one end pointed or flattened, the forerunner of the spade. It is not only found in early excavations everywhere, but is in extensive use today. Hoes were also used, with digging parts made of shells, flint, horn, and even wood. In some regions the primitive hoe is really a stick with the digging end flattened. The simplest form of hoe may be a wooden stick having a natural angle, as part of a small tree trunk with part of a projecting branch. A hoe made of two sticks of wood fastened together was characteristic of ancient Egypt about 3000 B.C. At Thebes, the ancient capital of Upper Egypt, we come upon another agricultural implement, the stone sickle, of the type used in the Nile Valley 4,000 years ago.

Agricultural improvement. Inasmuch as the beginning of agriculture far precedes any written accounts, the historical development of early husbandry remains unknown. However, archeological evidence indicates that for thousands of years improvements were gradual and rare, and seems to point to the Bronze Age (about 2000 B.C.) as the crucial turning point for betterment (Fig. 1).

Plowing scenes and fruit cultivation are depicted on Egyptian papyri of the fifteenth and fourteenth centuries B.C. Semple (1921) has pointed out that by 1500 B.C. Egypt had raised irrigated crops of wheat, barley, and millet far beyond the needs of the local population, thus enabling that ancient country to develop a grain trade with the Eastern Basin of the Mediterranean, a region having scant and irregular rainfall.

According to King (1911), between the years of 2737 and 2600 B.C. the plow was invented and silk culture originated in China. From the facts contained in Exodus 23:10 and 11, which is one of the oldest written records pertaining to agriculture, one may infer that prior to 1500 B.C., husbandmen, having experienced the exhausting effects of continual cropping, instituted the resting or

[2] HILGARD, E. W. Soils, pp. 419-420. 1906.

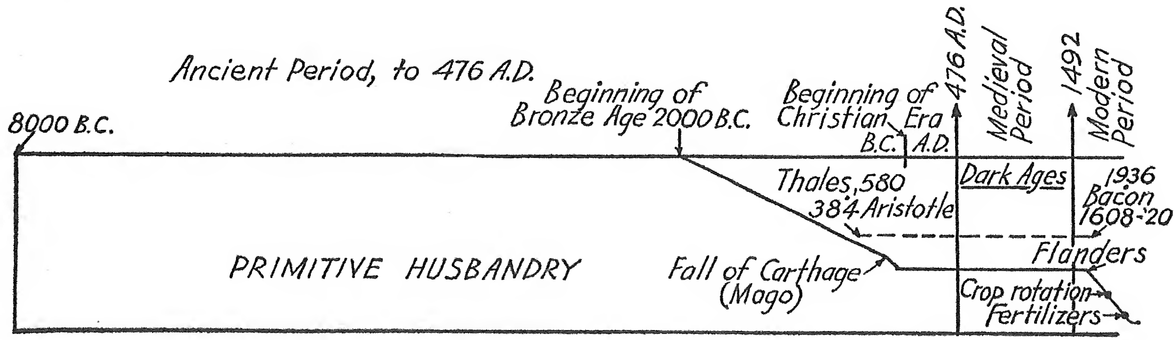

Fig. 1. Agriculture and scientific thought through the historical ages.

Primitive husbandry, which was dominant for 6,000 years, declined as thought and agriculture developed. But improvements were arrested before the close of the ancient period. From the fall of Rome (476 A.D.) to 1600, agriculture made no further progress. The background of ancient and medieval husbandry was wholly empirical. During the early years of the seventeenth century, Flanders became the school of agriculture for England and Europe. Then followed the development of modern agriculture with the adoption of proper rotation of crops (1730-1738) and the application of science (1840).

Scientific thought began with Thales (580 B.C.), but there was no linking of science with agriculture. Aristotle's thinking influenced the world for nearly 2,000 years. Agriculture, however, received no benefit from his philosophy, and there was little change until 1608-1620, when Bacon showed how the natural universalizing power of the human mind may be used to discover new knowledge, principles, and natural laws. It was Bacon who pointed the way to real scientific achievement, and in 1840 Liebig used inductive thought to bring science and agriculture together.

repose system for renewing the producing power of the earth. This principle was incorporated in the laws of the Israelites for governing their civil life on entering the Land of Promise. This law called for the resting of the land one year in seven, and no doubt gave rise to the custom of abandoning arable land at intervals to the natural growth of rough and weedy herbage.

According to Semple (1928), the climate of the ancient Mediterranean region caused winter to be the principal season of tillage, and summer a period of comparative rest. The rains usually sufficed for winter and spring crops. Owing to dry summers, the early Mediterranean husbandmen had to adapt their farming to the threat of limited rainfall. Thus dry farming developed: (a) in the north, a three-course farming system of winter cereals, spring cereals, and fallow; (b) in the south, a two-course system of spring cereals and fallow; and (c) discriminate use of lands based on the ability of soils to retain moisture.

Other improvements followed as knowledge regarding crop production increased. Hesiod, a Greek epic poet who died in 776 B.C., formulated rules for the husbandmen not only of his day but also of future generations, inasmuch as his precepts of husbandry were passed down through nearly nine centuries. According to Herodotus (Greek historian, 484-425 B.C.), cultivation of dates, which depends on a knowledge of fructification, was practiced by the Babylonians nearly 1,000 years before the Christian Era.

Green-manuring for soil improvement was first suggested by Xenophon, a Greek historian (430-355 B.C.). Bradley (Eng., 1727 A.D.) has quoted this historian as follows: "But then whatever Weeds are upon the Ground, being turned into the Earth, enrich the Soil as much as Dung." "When the Corn is come up and is high in the Blade, if you then turn it into the Ground with a Plow, it will greatly enrich the Land and give it as much Strength as a good Dunging would do."

Ancient farming at its best. History indicates that the best years of ancient husbandry were during the early years of the Christian Era when Rome was at her best. Immediately preceding and during this period much was written on agriculture by distinguished Roman authors, including Cato, Varro, Virgil, Columella, and Pliny

Cato, the Elder (234-149 B.C.), was bred to agriculture and wrote a convincingly practical handbook of husbandry entitled *De Re*

Rustica. He taught "intensive cultivation," crop rotation, the use of leguminous plants for soil improvement, the importance of livestock in farming, and preservation of manure. "What is the first principle of good agriculture?" he asked. "To plow well," he answered. "What is the second? To plow again; and the third is to manure."[3]

Cato attempted a classification of soils according to land utilization, as follows: (1) land for good vineyards; (2) well-watered garden land; (3) willow land; (4) land for olive yards; (5) meadow land; (6) corn land; (7) timber land; (8) land for small trees; and (9) land for acorn oaks.

Here mention should be made of Mago, the Carthaginian, who composed 28 books on agriculture. When the Romans destroyed Carthage in 146 B.C., Mago's works were taken to Rome and were translated into Latin by order of the Senate. These writings were regarded as standard authority. On them, more than 100 years later, Virgil based his elegant precepts of husbandry.

Varro (116-27 B.C.) emphasized the adaptability of crops to different kinds of lands. He also stressed green-manuring for rendering soils more fruitful, and he advised that land be planted lightly with some other less exhausting crop in lieu of fallowing.

Virgil (70-19 B.C.) taught the value of growing grains in rotation with legumes. He wrote:

> Where Vetches, Pulse and Tares have stood,
> and Stalks of Lupines grew (a stubborn wood)
> Th' ensuing Season, in return may bear
> The bearded Product of the Golden Year.

In practice, however, the Romans seem to have given little attention to crop rotation.

Columella (about 45 A.D.) stressed the high value of turnips in husbandry, and recommended that they be well manured, "For," he said, "it is of great importance, . . . because after a plentiful crop of them, ground thus managed bears excellent corn." He did not believe in permanent soil exhaustion, and strongly advocated soil improvement through drainage, growing clover and lucerne, and the use of dung, green manure (lupines), chalk or marl, and ashes. "The earth," he said, "neither grows old nor wears out, if it be dunged."

3 Cato's Farm Management, by A Virginian Farmer. 1910.

Pliny, the Elder (23-79 A.D.), like Columella, recommended green-manuring and the growing of turnips. In his book entitled *Natural History,* he assembled about all the ancients knew concerning tillage. But apparently he was conscious of a declining husbandry, resulting from the introduction of "destructive luxury" into Rome.

Fall of Rome. Rome and its institutions finally decayed. The classical civilization had run its course. Over most of Europe, Roman agriculture, the fruit of ancient husbandry, became submerged, owing to the irruptions of the barbarians of the North. Rome fell before the onslaught of people who knew nothing of the blessings of civil liberty, and for 11 centuries (to 1600) agriculture made no further progress in Europe. But, although improved husbandry had been abandoned generally, its traditions were preserved. In some favored regions removed from the climatic conditions of the Mediterranean Basin it was shaped, as in Flanders, in conformity with conditions of a humid climate, thus establishing the basis for modern Western agriculture.

RISE OF SCIENTIFIC THOUGHT

In considering the relation between agriculture and science, there are two concepts regarding scientific thought that should be clearly understood: namely, *science* and *scientific.* The term "science" conveys several meanings: (1) systematized knowledge of natural phenomena and their laws; (2) division or branch of organized knowledge, as geometry; (3) generalizations (principles or fundamentals) regarding natural phenomena; (4) fundamental facts, discovered scientifically, regarding natural phenomena; and (5) skill based on knowledge of principles. "Scientific" denotes mental and technical processes used in science building. The technical methods aid the mental processes. Such mental processes as observation (including tests), analysis, synthesis, imagination, supposition, deduction, inference, and induction are common to all sciences, which processes constitute the *groundwork of science.*[4]

The groundwork of the sciences, therefore, is mental. Normal human beings are naturally endowed with this groundwork. Principles or laws of natural phenomena constitute the heart of the sciences. Generalization, or induction (reasoning from particular to general), plays the most important role in the sciences. For

4 MIVART, ST. GEORGE. The Groundwork of Science. 1898.

example, what is found true regarding a few typical objects or phenomena of a given class is believed to be true for all members of that class. The distinguishing characteristics of a few typical dogs are believed to hold true for all dogs. What is found true for a few falling bodies is believed to be true for all falling bodies; therefore, it has been possible to discover and state the law of gravitation.

Generalization. Only individuals with highly trained minds can state the content of such general concepts as those indicated by common names like *cat, dog, pencil,* and *chair.* But generalization is an inherent power of the human mind. It is well developed in a normal 4-year-old child. Knowledge of only a few dogs, for example, enables the child to classify other dogs under the general concept of *dog.* This constitutes the first step in inductive thinking. The child cannot give the content of the concept named "dog," or define it, yet in a marvelous way he is able to discern certain distinguishing characteristics that are common to all dogs.

Primitive peoples exercised this natural power of generalization freely, inasmuch as each common noun of the languages that they developed is the name of a general concept that connotes what is common to all individuals classed under it. But a collection of class names is not science. A knowledge of the existence of certain natural bodies, such as different kinds of soils that are classed under the general concept of *soil,* is not science.

According to Lee (1921), a classification of the soils of certain thickly settled parts of China was made during the Yao dynasty during the period, 2357-2261 B.C., which included the following classes: (1) yellow and mellow; (2) red, clayey, rich; (3) whitish and rich; (4) salty; (5) mellow, rich, dark, and thin; (6) whitish and mellow; (7) blackish and rich; (8) greenish and light; and (9) miry soils. This was not a scientific classification, but rather simple, practical groupings of similar soils.

Science begins when, through the generalizing power of his mind, a thinking individual seeks to discover laws, or principles, regarding natural phenomena or to discover order in nature by means of classification.

Beginning of ancient science. Primitive peoples lived through thousands of years of myth and magic, while science was rising out of slow and unconscious observations of natural events. Such observations of the apparent movements of the heavenly bodies gave rise in time to astronomy and mathematics. Continued ob-

servations regarding natural phenomena gave rise to philosophy which involved not only astronomy and mathematics, but also the nature of matter (chemistry), origin of life (biology), properties of space (geometry), laws of thought and logical processes (logic), hydrostatics and levers (mechanics), and other sciences.

Ancient philosophy. The earliest systematic advances on the mythological concept of nature are those of Thales (580 B.C.), the founder of Greek philosophy, who intuitively discovered certain mathematical principles. Observing how plants were sustained by water, he inferred that water was the origin of all things.

Subsequent philosophers made further advances on the mythological view of nature. The great lights of the ancient pagan world were Socrates (470-399 B.C.), Plato (428-348 B.C.), and Aristotle (384-322 B.C.), who were responsible for the glorious period of Greek philosophy and gave dignity to intellectual inquiry.

Socrates broke down the basis of sophistic philosophy, or false science, which denied the existence of active Supreme Intelligence as the foundation of true science. He aimed to force seekers after truth to generalize inductively, for by this method alone could trustworthy conclusions be formed.

Plato laid particular stress upon first cause as the logical basis of true science—eternal truth, one God. Both he and Aristotle taught that science can be developed only by reason.

Aristotle is called the "father of logic." Realizing the tendency of human beings to make rash general statements, he attempted to check this tendency by setting up a severe standard for generalization, based on an examination of the whole class concerned. This standard was a logical scheme, called the "syllogism," which he believed should be the scientific method. This standard may be illustrated as follows:

Syllogism, a form of inference	All living plants absorb water;	(Major premise, the universal)
	A tree is a living plant;	(Minor premise)
	Therefore, a tree absorbs water.	(Conclusion)

The syllogism has long since been rejected, for as Bowne (1897) has pointed out, it leads to no new knowledge. "A universal reached by simple summation would not be any rule for thought, but merely a dead register of experience." A generalization is not reached in that way, but rather by induction—that is, by taking certain cases as typical and from them inferring a law that holds

true for the whole class. Aristotle reasoned without sufficient certainty for the generalization of his syllogism. His method proved to be no aid to science; instead, it led to a spirit of useless quibbling. Nevertheless, his philosophy influenced the world for 2,000 years, through the Middle Ages and down to the time of Francis Bacon (Eng., about 1561-1626 A.D.). (Fig. 1.)

MEDIEVAL AGRICULTURE

Agriculture during the Middle Ages was characterized by a 3-field or triennial system of cropping in which the manor was the unit of land-holding and cultivation. In this system a 3-year rotation predominated: (1) winter grain (wheat or rye); (2) spring "corn" (barley, oats, peas or beans, or mixed grains); and (3) bare fallow. Each field was cultivated by many tenants, each having a certain number of scattered 1-acre or half-acre strips separated by "balks" of rough grass. Thus on a given field it was necessary for all the tenants to sow the same crop, plant at the same time, and harvest together. After harvest the cattle were allowed to wander over the fields, thus preventing the growing of any fall cover or fodder crops. The manor aimed to be self-sustaining as to both food and clothing.

The meadows, divided as were the fields, were used for hay; and after haying, for pasturing in common. The fallow field was pastured in like manner. Each manor included more or less waste land on which the tenants held in common the right of pasturage.

In general, in this system may be found the principal features of Roman husbandry: namely, fallowing, manuring (in a limited way), chalking or marling (in places), alternate cropping, growing legumes (peas and beans), and pasturing livestock. But farming under the conditions of those times, when life and property were insecure, was very inefficient. Moreover, the environment, particularly during the first two or three centuries of the so-called "Dark Ages," was very discouraging to thought.

Crop yields were determined largely by the natural producing power of the land. Crops were poor, as is indicated by an average yield of wheat in England during this period of 6 to 10 bushels an acre. However, the manorial system during the age of political feudalism, when the functions of the State were transferred from central authority and exercised by overlords, was largely the cause of this underproduction.

MODERN AGRICULTURE AND SCIENCE

The state of husbandry during the first century of the modern era remained practically unchanged, except that in late medieval times enclosures began to break into the manorial system. FitzHerbert (Eng., 1523), in his work entitled *Boke of Husbandry,* severely criticized the 3-field system. But not until the governments of the new Western civilization began to be founded upon more fixed and rational plans, and property became secure, did agriculture, with other arts, rear its head. Courage born of knowledge was needed in those days. During the Renaissance, new learning awakened free thought, printing was applied to the diffusion of knowledge, and a newly aroused curiosity about nature encouraged the development of scientific thought.

Rise of science and agriculture. Ancient and medieval husbandry was wholly empirical, whereas modern agriculture, for the most part, is scientific. The modern age is preëminently scientific, owing largely to the philosophy of the new experimental method formulated by Bacon.

Bacon, regarding the Aristotelian standard of inquiry as wrong, proposed the use of the inductive method for acquiring new knowledge, for finding explanations of natural phenomena, and for discovering natural laws. In analyzing the working of the human mind, he was led to the conclusion that the same generalizing power (inductive thinking) that human beings have always used in forming general concepts of things about them was the logical groundwork of science.

The method Bacon proposed insisted on dismissal of all prejudices and preconceptions, and on close and systematic observation of the facts concerned. It called for the taking of a few typical or specimen cases, and inferring from them a law for the whole class. Although Bacon did not invent nor discover induction—for that is a natural power of the human mind—he showed the right way to use this marvelous generalizing power for discovering principles and laws regarding natural phenomena. By so doing, he broke, as it were, the shackles of Aristotelian thought, which had held for 2,000 years. The experimental method has since become the great cause of modern progress in science.

The scientific method. According to Bacon, the steps in investigation may be stated as follows: (1) unbiased gathering of facts

into classes relevant to the matter in hand; (2) formulation of hypotheses based on typical facts; (3) examination of explanation or hypotheses implied in additional facts; (4) elimination of additional facts or hypotheses; and (5) verification of one remaining generalization.

With present knowledge of certain natural laws, a simpler scheme has become the common method of research: namely, (1) observation of facts and formation of hypothesis (in harmony with known laws); (2) deduction of conclusions from the hypothesis; and (3) experimentation or comparison of inferred facts with those observed. In science inductive reasoning plays the most important role, and the methods of the different sciences are, in the main, instruments of induction or aids thereto.

Philosophically, "Bacon was an architect, not a builder." There were "builders" before and during his time—Roger Bacon, Copernicus, Brahe, Gilbert, Kepler, Galileo, and Harvey. Nevertheless, Bacon described the thought technique for discovering order in nature and for discovering natural laws; but it was left for others to appreciate its value. Immediate progress from Bacon's new philosophy was impeded by civil disturbances in England. But after the founding of the Royal Society for the Improvement of Natural Knowledge in England in 1660 by devout Baconians, systematic and fruitful scientific labors began.

Development of chemistry and of a new agriculture. During the first half of the seventeenth century, there began two distinct developments the ultimate effects of which on husbandry were profound: namely, (1) evolution of a new agriculture, and (2) a systematic inquiry into plant nutrition which was made possible through the development of chemistry. Each development proceeded independently of the other for about 200 years, until 1840, when Liebig (Ger.) made his pronouncements that established agriculture on a scientific basis.

The new agriculture. During the early 1600's several new ideas regarding husbandry were introduced into England from Flanders. Among these were elimination of the bare fallow, growing of clover and other sown grasses, also of turnip and rape, and the production of 6 crops in 6 years on a given field instead of only 4. Improved seeds and better livestock, deeper tillage, and different succession of crops were other features of the new husbandry.

Evidently the Flemish farmers had abolished the fallow at a

very early date, and substituted the growing of clover and other legumes in rotation with turnips, small grains, and hemp. Such a system made possible more intensive cultivation to meet the food problem, and it made possible also the keeping of more livestock and the development of a more productive agriculture. For nearly a century Flemish methods made little progress in England, owing to the strongly intrenched 3-field, or Roman triennial, system. Some of the early agricultural writers have mentioned a serious weed problem, which was probably an additional factor involved.

Intertillage. Introduction of intertillage of field crops marks another stage in improved husbandry. In Flemish, as in ancient and medieval husbandry, all field crops were planted broadcast. Although the art of hoeing in between garden and vineyard plants had been practiced from time immemorial, it had never been applied to field crops until Jethro Tull (Eng., 1731), having proved the value of intertillage, introduced into English husbandry the idea of planting certain crops like turnips in rows to allow "horse-hoeing," as he called it. He thus broke a 97-century-old farming practice, and introduced a new order in husbandry. Tull successfully practiced intertillage on his own farm, but for many years his ideas were regarded as speculative innovations. His methods necessitated a new device for planting, the drill, which he invented in 1701.

Norfolk rotation of crops. Another great improvement in husbandry was made when the Norfolk system of cropping was established by Lord Townshend of Norfolk County, England, during the period between 1730 and 1738. This system included 2 small-grain crops, turnips as an intertilled crop and clover, and the use of farmyard manure. The new scheme was a 4-course rotation of wheat, turnips, barley, and clover or beans (grown in the order named), which afterwards became known as the "Norfolk rotation." This marked the beginning of a general agricultural revival. England now became the school of agriculture for both Europe and America. Under this new system, the average yield of wheat in England was raised from about 8 bushels, the average for medieval times, up to 20 bushels an acre by 1840 (Fig. 2).

Simultaneously with the improvement in the system of cropping, other improvements were in progress in Europe, and forces developed which proved to be most effective in promoting agriculture.

These forces included improvement of livestock in England between 1760 and 1836, and land drainage between 1823 and 1874. The outstanding leaders in husbandry at this time were Arthur Young (Eng., 1768-1811), Leicester of Holkham (Eng., 1772-1842),

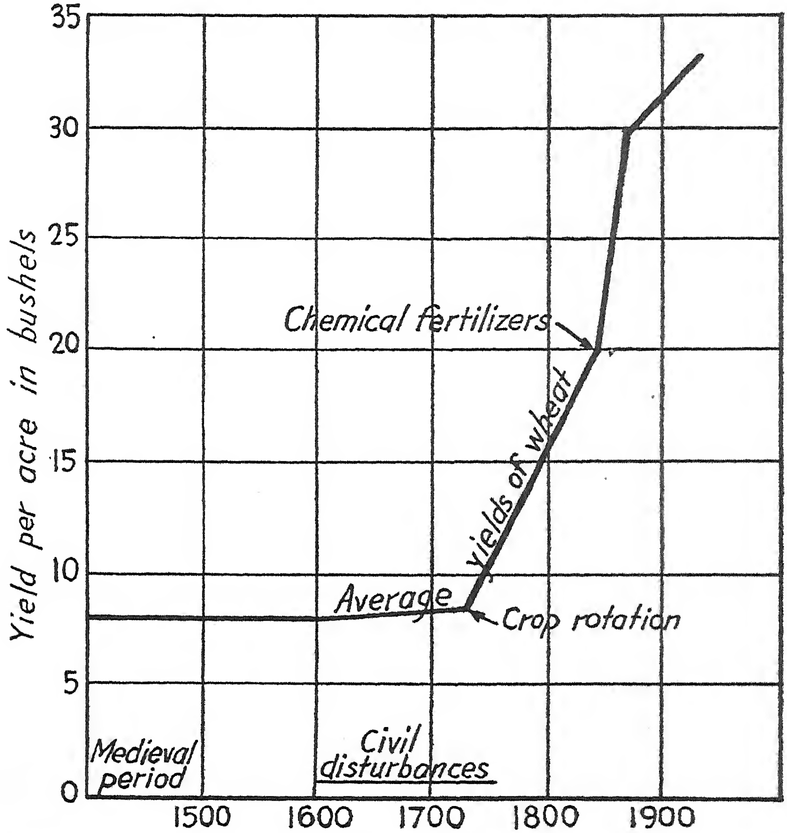

Fig. 2. Trend of average yields of wheat in England, showing the relation to events that affected agricultural improvements.

Thaer in Germany (1798-1812), Sir Humphry Davy (Eng., 1813), and members of the Royal Agricultural Society (1838).

In his book entitled *Rural Economy,* Arthur Young (1770) recognized the great value of livestock in farming, and he anticipated the use of artificial fertilizers. He wrote: "Without plenty of cattle there can be no good husbandry." "Who knows but there may, in the walk of agriculture, be compound manures pow-

erful enough to give fertility to the earth vastly greater than anything we at present know of."

Inquiry into plant nutrition. Inquiry into plant nutrition developed with chemistry, a science evolved from alchemy (the pretended art of converting base metals into nobler ones like gold) which probably originated in ancient Egypt. The prefix "al" began to be dropped about the middle of the sixteenth century, giving rise to the term "chemistry." Between 1635 and 1682, the theory of phlogiston developed. According to this theory, every combustible substance was composed of "phlogiston" (material of fire), and combustion was the result of the phlogiston leaving the other constituents such as ashes or oxide behind. The year 1661 marks the beginning of the modern science of chemistry, when Boyle (Eng.) published his book entitled *Sceptical Chymist.*

The phlogiston doctrine, which involved the old Greek Elements of Water and Air and Earth, dominated chemical thought for over a century, until 1777, when Lavoisier (Fr.), by the use of a balance, showed that combustion was the result of the combining of a burning substance with oxygen. In the brilliant experiments of Lavoisier and of Cavendish (Eng., 1785), the Phlogistic Theory met its death blow. Based on Lavoisier's oxygen theory, there evolved a new concept regarding structural elemental units, as opposed to the old Greek ideas. Rapid development in both chemical thought and research methods followed.

With this brief sketch of the history of chemistry, we can better appreciate the difficulties that the early investigators experienced in their search for plant nutrients.

Regarding water. In 1620, Van Helmont, a noted Flemish alchemist, conducted an experiment with a willow shoot, and concluded that water was the only plant nutrient. It is plain that he did not know the importance of making further observations, of introducing other hypotheses, and of canceling incorrect explanations. Nearly 80 years later, Woodward (Eng., 1699) conducted water-culture and pot tests, and disproved Van Helmont's conclusion by showing that plants required something more than just water. Subsequently, the true relation of water to plant nutrition was shown by Cavendish, when he discovered its composition of oxygen and hydrogen.

Nitrogen, phosphorus, and potassium. The three major fertilizing elements—nitrogen, phosphorus, and potassium—were known

many years before Liebig put agriculture on a scientific basis. Nitrogen was recognized as "foul air" by Scheele (Swed.), a phlogistic chemist, in 1772. In 1774, Lavoisier called this foul air *azote* which was later named "nitrogen" (from niter). The element phosphorus was first obtained in 1669, and in 1775 Scheele prepared it from bones. The element potassium was isolated in 1807 by Sir Humphry Davy from "potash" (pot ashes) which was long regarded as an element in itself.

In some early experiments it was shown that certain waste substances, such as manures, composts, and ashes, favored plant growth, and this agreed with the practical experience of husbandmen. In 1656 Glauber, a German medical alchemist in Holland, found that nitrates stimulated plant growth; and 100 years later Home (Scot., 1756) made a similar discovery regarding potash, Epsom salts, and saltpeter. From crude analyses of plants, Wallerius (Swed., 1761) concluded that "humus" was the nutrient of plants. Later, Leicester of Holkham (Eng., 1772) found that field crops responded to crushed bones, and the Earl of Dundonald (Eng., 1795) showed the usefulness of alkaline phosphates in plant growth.

So far as is known, Leicester of Holkham ("Coke" of Norfolk) was the only one who made practical use of new knowledge gained regarding the use of simple chemical substances for fertilizing plants. An old idea that plants required substances corresponding to their own nature continued to hold sway.

Oxygen, carbon dioxide, plant ash. In 1772, Priestley (Eng.) found that respiration of animals "deteriorated" the air, whereas plants renewed its power to support combustion; but he was unable to give an explanation. Shortly after, simultaneously with Scheele, he discovered oxygen, which he called "dephlogisticated air." Priestley also discovered ammonia (1774), which he called "alkaline air." In 1777, Scheele found that this alkaline air contained *azote* (nitrogen).

Since 1774, inquiry into plant nutrition developed according to the new concept of structural elemental units and through the aid of quantitative methods. In 1779, Ingen-Housz, a Dutch scientist at Geneva, laid the foundation of chemical plant physiology by showing that plants assimilated the carbon dioxide from the atmosphere and released oxygen to the air in daylight, and that the reverse process took place in darkness, although to a less degree. He

also showed that plants oxidized the organic compound during respiration, and that they disposed of the waste carbon as carbon dioxide.

In 1804, De Saussure (Switz.), adopting the precise methods of Lavoisier, supplied the quantitative proof of the chemical equation involved in the assimilation of carbon dioxide by plants. He recognized nitrogen as an important constituent of plants, and also the value and source of plant-ash, or mineral, constituents. He thought that the source of the nitrogen in plants was either the organic matter in soils or atmospheric ammonia. It was De Saussure who first observed that ammonium salts stimulated plant growth. But the significance of these findings was entirely overlooked, even though De Saussure (1804) had summarized all the results obtained in plant-nutrition inquiry in his book entitled *Recherches Chimique sur la Végétation.* Here attention is called to the fact that the ''humus'' theory of plant nutrition had long been dominant.

Field experiments. Thirty years passed, and a new method of inquiry was inaugurated: namely, field experiments. To Boussingault (Fr.) belongs the credit of introducing this important method of agricultural research. In 1834 he laid out plots and began a systematic, physiological study of the action and value of ''manures'' on crop plants that were grown in rotation with clover.

Agriculture established on the scientific basis. In 1838, Liebig, a brilliant German chemist, turned his attention from pure chemistry and began studies of animal and plant physiology, seeking to discover the laws of the natural phenomena concerned. He organized the scattered facts of practical husbandry and of plant nutrition into a connected whole; and with these correlated facts in hand, he exploded old theories, explained certain phenomena, formulated hypotheses, and inferred certain natural laws, which he set forth (1840) in his famous book entitled *Die Chemie in ihrer Anwendung auf Agriculture und Physiologie.* He thereby established a scientific basis for agriculture, which had been empirical for more than 98 centuries. His book stimulated fervent inquiry into agricultural problems.

From the early use of manure by the ancients, there had developed a belief that plants required food of organic origin, food which corresponded with their own nature. Thus natural manures

were regarded as the proper food material for crop plants. This became known as the "humus theory of plant nutrition." Liebig rejected this theory, and gave it a death blow. He taught that plants derived their carbon and nitrogen, respectively, from the carbon dioxide and ammonia present in the atmosphere, and that they obtained their ash or mineral elements from soils. Most important of all was his inference that plants absorbed simple substances like water, carbon dioxide, ammonia, and mineral substances, converting them into complex organic compounds.

Events leading to discovery of chemical fertilizers. So far as the nutritional requirements of plants were concerned, Liebig concluded that there could be no exhaustion of carbon and ammonia, as the supplies in the air were constantly renewed by putrefaction and fermentation; whereas the supplies of mineral elements in the soils were limited. He taught that the function of fertilizing materials was to restore to soils the ash constituents, or mineral elements, removed by crops. Liebig's thesis suggested to him the application of the so-called "law of diminishing returns" and the "law of the minimum" to plant nutrition, stated as follows:

"The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure." "By the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable."

On his theory of the function of fertilizing materials, Liebig prepared artificial or mineral fertilizers which contained the essential plant-ash constituents plus a small quantity of ammonium salts. With these he initiated systematic experiments on a small 10-acre farm of poor, sandy land, but results were discouraging. He made two serious mistakes: (1) he discredited nitrogen in his mixtures; and (2) fearing that the alkalies would leach from the soils and thereby be lost to the crops, he subjected them to a fusion process in order to convert them into insoluble forms before application. This was unsuccessful.

Lawes (Eng., 1843), in his experiments at Rothamsted, definitely proved the first error in Liebig's procedure by demonstrating with wheat the value of including adequate ammonium salts in chemical manures. Way (Eng., 1850) pointed out Liebig's second error,

and showed that the fusion process was not only harmful, but also needless, inasmuch as nutrient elements must be in available form and inasmuch as soils have absorbing and retaining powers.

Liebig made mistakes, but in his time scientific thought regarding agriculture needed the forceful logic of this outstanding genius to change the point of view pertaining to a fundamental problem of crop production. Humanity had already given expression to its fear of facing food shortage through Thomas R. Malthus (Eng.), who, in 1798, advanced the theory that population increased at a faster rate than the means of subsistance. Liebig's inference that higher plants took in simple mineral and gaseous substances and out of them manufactured complex organic compounds had tremendous significance. This hypothesis, which he failed to prove but which has since been established as a phenomenal law, has become a great foundation stone of modern agriculture. It has given humanity the assurance of a permanent food supply.

Chemical manures, a scientific achievement. About the time Liebig began his physiological studies with crop plants, John Bennet Lawes of Rothamsted, England, began pot experiments with various "manures," including guano, nitrate of soda, bone dust, farmyard manure, potassium salts, and ammonium salts. Nitrate of soda and guano were introduced for experimental purposes into England from South America in 1835 and 1841, respectively; Davy had already analyzed guano (1805) and found it to consist of one third ammonical salts and other salts and carbon.

In 1839 Lawes carried his experiments to his fields, for of necessity, he was particularly interested in growing more and better turnips for his sheep. He tried bone dust (crushed bones) which some leading farmers had already used with marked success. Leicester of Holkham ("Coke" of Norfolk) had profited much from the use of ground bones. But Lawes' turnips failed to respond satisfactorily. Knowing the chemical nature of bones, he decided to make the phosphate contained therein soluble by treating the bones with sulphuric acid, thereby producing superphosphate. The results of his tests with superphosphate proved to be so satisfactory that he applied the same acid treatment to rock phosphate (apatite). Realizing the practical value of his discovery, he patented the superphosphate (1842), and the following year began the manufacture of chemical fertilizers. The same year

(1843) he engaged the services of J. H. Gilbert, and also founded the Rothamsted Experimental Station.

Lawes realized another outstanding scientific achievement. He proved the fertilizing value of mixtures of chemical salts. He had become deeply interested in the work of Liebig. But, although he believed that plants required the mineral elements found in plant ash, he did not accept Liebig's theory regarding the source of nitrogen in plant nutrition. Accordingly, he initiated experiments on wheat and showed (1843) that a chemical mixture containing ammonium salts gave higher yields of grain and straw than ashes of farmyard manure, but without ammonium salts.

Scientific progress. The year 1840 marks the beginning of scientific agriculture. The effects produced may be measured in terms of the average wheat yield of England, which was raised from 20 to 30 bushels an acre by 1870. The average is now about 33 bushels. It took more than 100 years for the new husbandry embodied in the Norfolk rotation to raise the average yield of about 8 bushels of medieval England up to 20 bushels, whereas it required only 30 years for scientific methods to add 10 additional but more difficult bushels to the average yield. (Fig. 2.)

Improvements were not confined to England and continental Europe. The new knowledge of crop production and of the use of chemical and commercial fertilizers was diffused throughout the world.

Agricultural colleges and experiment stations. Agricultural experiment stations and colleges have been two important agencies in furthering the development of scientific agriculture and in diffusing useful scientific knowledge. The first agricultural experiment station was established at Rothamsted, England, in 1843. This pioneer institution remained solitary and unaided for many years, although the methods it developed according to scientific principles had been accepted and applied to agriculture in many countries. In Great Britain systematic agricultural education began about 1890, although chairs of agriculture and rural economy were established at Edinburgh in 1790 and at Oxford 6 years later, and the Royal Agricultural College at Cirencester (Eng.) was chartered in 1845.

In the United States, John P. Norton began scientific studies of agriculture at Yale University in 1847, which studies were continued by Samuel Johnson. Systematic teaching of agriculture had its

beginning in 1821, in Maine. Agricultural schools were founded in Connecticut in 1826 and in New York State from 1825 to 1840. State agricultural colleges were established in New York in 1853, at East Lansing, Mich., in 1857, in Pennsylvania and Maryland in 1859; and incorporated colleges were organized in Iowa and Minnesota in 1858. The first Morrill Act, which created land-grant colleges, was signed by President Lincoln in 1862, the same year in which the United States Department of Agriculture was organized.

In 1887 the Hatch Act was passed, providing for the establishment of agricultural experiment stations as departments of State colleges. Prior to 1887, State experiment stations had been established in 19 States.

Modern research. The trend in modern agricultural research is toward group inquiry; that is, the solution of a particular problem may involve the joint research of several investigators, each correlating his work with that of the others. The solution of many problems requires this kind of teamwork. Inasmuch as soil fertility implies relationship between soils and crop plants, the successful solution of a soil-fertility problem may call for the teamwork of a group of scientists, including a pedologist, soil physicist, soil chemist, soil microbiologist, plant physiologist, and a statistician or biometrician.

Although, since 1840, agriculture has become dominated by science, no science of agriculture has been created. The reason is plain. The field is altogether too broad and embraces too many quite different subjects—such as soils and their fertility, field crops, horticulture, animal husbandry, and economics—to make possible the discovery of fundamentals or laws which might be regarded as principles of agriculture. However, much knowledge relating to the various agricultural subjects has been accumulated; and the general or fundamental facts, through inductive thought, have served as guide posts in pointing the way to the discovery of principles and laws which may form the bases of a number of agriculture sciences. Such a development of knowledge has given rise to this present work—"Soil Science."

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REVIEW QUESTIONS

1. Why should the beginning and early development of agriculture be discussed as a fitting introduction to the subject of soil science?
2. Sketch the development of agriculture from its beginning to the present time, stating only the most important improvements in each historical period.
3. How did the thinking on agricultural problems differ during these historical periods?
4. Climatically, trace briefly the development of agriculture and give reasons for such a development.
5. Discuss Roman agriculture and its bearing on modern farming.
6. What are the essential features of the sciences? Of soil science? Define soil science. (See Preface.)
7. What kind of thinking is commonly regarded as the most important in the sciences? Discuss and illustrate.
8. What is the difference between Aristotle's and Francis Bacon's theories regarding scientific thought?
9. Discuss the relationships of agriculture and chemistry between the early 1600's and 1840.
10. Explain why Liebig is given the credit for establishing agriculture on a scientific basis.
11. Who established the practice of supplying crop plants with nutrient elements through the use of chemical fertilizers, and how?
12. Name some of the important agencies that aid the development of scientific agriculture.
13. What is the trend in modern agricultural research?
14. What is the difference between facts and principles regarding natural phenomena?
15. Was Jethro Tull a scientific man?
16. Was the Norfolk system of cropping a scientific achievement?
17. With the help of the Contents, illustrate briefly with diagram or outline the concept of soil science as it is expressed in this book.

CHAPTER 2

PHYSICAL CONSTITUTION OF SOILS

Inasmuch as the purpose of a science is an understanding of the things concerned, the logical first step in soil science is to gain knowledge about soils themselves, which is prerequisite to a clear understanding of them and their relation to plant growth and crop production. This calls for general facts that are basic or fundamental about the make-up of soils, their physical properties, chemical nature, and their microbial population.

Although soils seem to be simple earthy bodies, which even primitive peoples have used for producing food crops, they are, in fact, very complex, principally because of their threefold nature—physical, chemical, and biological. Moreover, soils are of innumerable kinds, and they usually vary widely within each kind. Thus in soil science we are confronted with multiformity, common in nature. But in this diversity, as in other natural sciences, we endeavor to simplify thinking through generalization and classification.

A remarkable general fact to keep in mind—one to which many facts are related—is that a normal soil provides plants with an aërated root zone, with water which must be replenished without impeding aëration, and with a continuous supply of nutrients.

PHYSICAL FRAMEWORK OF SOILS

The physical framework of soils consists of clay, silt, sand, gravel, stones, and organic matter, intermingled. The separate particles vary widely in size and shape. The physical make-up of a mineral soil may be described in terms of *mechanical composition,* as ascertained by *mechanical analysis.* This process consists in sorting out the soil particles into fractions or separates of different coarseness and fineness, thus providing a basis for a mathematical expression of textural qualities such as loam, sand, silt loam, and sandy loam.

Classification of particles. According to international agreement among soil scientists, soil fractions are grouped as shown in the following tabulation.

Soil-Fraction Group by Diameter of Particles	German Name	English Name
Less than 0.002 millimeter in diameter........	Schlamm, Ton	Clay
From 0.002 to 0.02 millimeter................	Schluff, Staub	Silt
From 0.02 to 0.2 millimeter..................	Mo	Fine sand
From 0.2 to 2.0 millimeters..................	Sand	Coarse sand
Greater than 2 millimeters...................	Kies	Stones

According to standards in the United States, silt particles range in diameter from 0.002 to 0.05 millimeter; sand particles from 0.05 to 1 millimeter; and fine gravel from 1 to 2 millimeters in diameter.

Coarse sand, fine sand, and probably coarse silt consist principally of unaltered, rock-forming mineral particles, such as silicates (feldspars and hornblendes) and quartz.

Clay particles differ from sand and silt in two essential features: (1) They originate through chemical action in rock weathering, and (2) they constitute the colloidal materials in soils, which are commonly called *soil colloids.* The finest clay particles are exceedingly small—3 microns or less in diameter.[1] Some clay particles are so small as to be microscopically invisible, like those of ultraclay.

Rock fragments of various sizes may also occur in soils, as follows:

Rock grains; angular fragments (from 1 to 5 or more mm. in diam.).

Gravel; roundish fragments (from 2 mm. to 2.5 in. in diam.).

Stones; rock fragments from 2.5 inches to moderate size.

Cobblestones; naturally rounded stones (2.5 in. to 10.5 in. in diam.).

Boulders; large, detached, rounded rocks (more than 10.5 in. in diam.).

Colloidal materials. Discussion of the physical nature of the clay fraction will be continued under the subject of "colloidal materials," as this is the term that commonly appears in scientific literature.

Hilgard (1873) and Schloesing (Fr., 1874) were the first investigators to call attention to the colloidal materials in soils, to which they attributed the quality of *plasticity*.

What constitute soil colloids. There is no sharp dividing line between colloidal and noncolloidal soil materials, nor has any upper limit of colloidal size been generally agreed upon. Probably

[1] A micron is a thousandth part of 1 millimeter. Its symbol is μ.

the colloidal property of soil materials is not wholly due to size of particles; chemical composition may also be a factor, inasmuch as sodium clays are very sticky, as compared with calcium clays.

Quantity of colloids in soils. Owing to their gluey nature, the separation of colloids from other soil constituents is difficult. On the basis of the absorption of dye, water, and ammonia, Gile (1924) found the content of colloidal matter of a gel-like nature in 32 different soils to vary from 6 to 70 percent. The colloids of some soils consist mostly of inorganic matter; whereas in some peat soils, they are primarily organic substances. Some dark-colored soils contain large amounts of both organic and inorganic colloidal materials. These plastic substances give to soils those colloidal properties that are so important in fertility, playing a major role in plant nutrition and crop production.

How colloids exist in soils. Gile concluded that colloidal matter could not be present in soils except as films or coatings around the larger particles. Anderson and Mattson (1926), on the other hand, have concluded that colloidal materials exist in soils principally as gels—that is, as intimate aggregations of ultimate particles. When colloidal material is dispersed in water, the dilute *sol* is stable, although the suspended matter may consist of both ultimate particles and aggregates of them.

Mechanical composition and use of land. The mechanical composition of soils varies widely, as one may judge from such soil descriptive terms as "coarse sand" and "heavy clay." There is a close relationship between the mechanical composition of soils and their suitability for crops.

Hall and Russell (Eng., 1911) have published some valuable data to illustrate the relationship that may exist between mechanical composition of soils and crop adaptation, as follows:

RELATION BETWEEN MECHANICAL COMPOSITION OF SOILS AND CROP ADAPTATION [2]

Soils	Soil Separates or Fractions					
	Fine Gravel	Coarse Sand	Fine Sand	Silt	Fine Silt	Clay
	Percent	Percent	Percent	Percent	Percent	Percent
Eight typical potato soils....	0.9	20.6	45.2	10.8	6.0	9.0
Ten typical barley soils.....	1.2	16.6	30.2	18.4	7.9	13.1
Seven typical wheat soils....	1.5	4.0	24.4	22.9	13.3	18.7

2 HALL, A. D., and RUSSELL, E. J. A Report on the Agriculture and Soils of Kent, Surrey, and Sussex Counties, England. 1911.

The explanation for the difference in crop adaptation is not to be found simply in the difference in mechanical composition, but rather largely in the difference in the textural qualities of the soils resulting in consequence of the different proportions of sand, silt, and clay. The soils suitable for potato crops are open, early, warm, well drained, and aërated, and they allow tuber growth without cracking. The wheat soils, on the other hand, are more compact, cooler, have greater water-holding power, and have the ability to satisfy the requirements of the wheat plants. According to Hall and Russell, wheat does best on firm and "tight" soils, and barley soils should contain about 10 percent coarse sand to keep them open, and not more than about 16 percent clay.

Organic matter. Most of the organic matter of a soil is contained in the topsoil, although in some soils a certain quantity of the organic matter has been carried down into the subsoils. Aside from micro-organisms, practically all soil organic matter is derived from plants, and is present in various stages of decomposition. Organic matter supplied to soils by recent growth of vegetation may be classed as follows: (1) material that still retains its cell structure; (2) organic matter partly decomposed and in process of decomposition; (3) soluble substances that result from decomposition; and (4) undecomposable plant and animal constituents.

Humus
Chapt 10

The term "humus" is sometimes used in a general sense to designate soil organic matter. As a matter of fact, "humus" is a name given to a group of black, sticky or waxy, complex compounds that are derived from organic matter originating from substances that have been synthesized by plants. These include lignins, proteins, tannins, chlorophyll, pigments, vegetable fats, and resins. Accordingly, the term "humus" may be used in a collective sense. The fact that humus may accumulate in soils indicates its high resistance to decomposition.

Organic matter, particularly humus, affects many of the properties of soils, notably color, structure, and tilth. Organic matter, in relation to soil fertility, is discussed fully in Chapter 18.

SOIL WATER

The sources of soil water are rainfall, reservoirs, and in some places, ground water which becomes available through "capillar-

ity." The losses occur through drainage, evaporation from the ground surface, and through transpiration by plants.

Briggs (1897) suggested that soil water from saturation to dryness could be designated as *gravitational, capillary,* and *hygroscopic.* These division names do not imply that breaks occur between the different forms or stages of soil water. On the contrary, soil water is continuous from the saturation state to dryness, as has been definitely established by Keen (Eng., 1914, 1920). Assuming that mineral soil particles constitute an inert framework, he has described three stages of soil water—*capillary, funicular,*

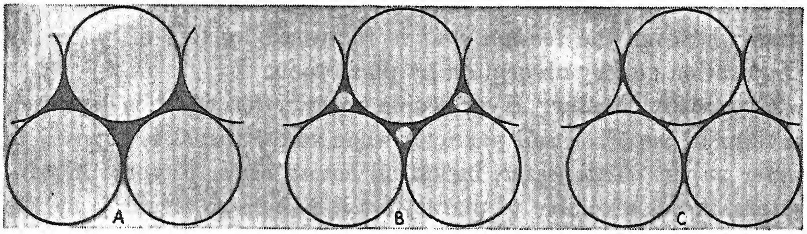

Fig. 3. Three stages of soil water: A, capillary; B, funicular; C, pendular.

and *pendular*—showing the continuity of the water through the three arbitrary divisions suggested by Briggs (Fig. 3). In the capillary stage the pore spaces between the soil particles are completely filled with water, indicating saturation. In the funicular stage, the water "wedges" are in contact, establishing continuous liquid-phase contact around the soil particles. In this stage, water can percolate through a soil without saturating it. The pendular stage refers to discrete rings of water, one around each contact point between any two soil particles, the contact point being the center of the moisture ring. As Keen has pointed out, it is obvious that these three stages of soil water can exist side by side.

Basic concepts. A knowledge of a few basic concepts will give one a clearer idea of soil water, to wit: *Ground water* (basic or bottom water) occurs in the underground zone of saturation, the upper limits of which is the *ground-water table.* Above the water table to the ground surface is the *zone of aëration,* in which water is held against gravity. Immediately above the water table is a *capillary fringe* in which water is held by tube or true capillarity.

Gravitational water. Water that flows downward by gravity through a soil or zone of aëration is designated as gravitational.

The term "free water" is applied by hydrologists to the free-moving ground water below the water table. The quantity of gravitational water that soils can hold when saturated varies from 40 to 60 percent of the total soil pore space.

Capillary water. In a broad sense, capillary water, which contributed most of the water used by plants, is water held against the force of gravity in the zone of aëration above the water table; whereas the term "pellicular" is applied to water that is held against gravity in the zone of aëration above the capillary fringe, which corresponds to Keen's *funicular* water. Pellicular water exists as films over the soil particles. Movement of this water results whenever the *tension pull* is increased by loss of water by evaporation and by absorption by plant roots.

Hygroscopic water. Hygroscopic water is that which is deposited as films of vapor on soil particles when soil material is exposed to water vapor. This water, including *bound water* of some investigators, is not available to plants, for it is held so strongly by the soil particles that it can be driven off only by heat.

Soil water v. soil moisture. Water diffused in a soil as sensible dampness is designated as *moisture,* and it includes water that is held in the zone of aëration above the capillary fringe.

Equilibrium points. In the investigation by Briggs, it was the aim to measure the quantity of water that may be held back by a soil from plant roots when the forces that ordinarily draw water into the roots and those that hold it in a soil are in equilibrium. By whirling soil material with enormous rapidity in a centrifuge, Briggs and McLane (1907) found that the water-holding power of a soil material was equivalent to about 0.001 atmosphere, or about 1,000 times that of gravity. This equilibrium point, or the moisture held in soil material against this centrifugal force, they called *moisture equivalent.* Typical values for this equivalent, based on the dry weights of soil materials, follow:

Texture	Percent
Sand	3.6
Fine sand	4.3
Sandy-loam material	10.3
Fine-sandy-loam material	12.3
Silt-loam material	19.8
Clay-loam material	23.1

After investigating this problem further, Briggs and Shantz (1912) suggested certain other equilibrium points, in order to give precision to the division between hygroscopic and capillary forms of soil water: namely, *wilting coefficient* and *hygroscopic coefficient*. The former term means the moisture content of soil material at which plants permanently wilt. They concluded that for a given soil texture the wilting coefficient was practically the same for all crop plants. Other investigators have found that this does not

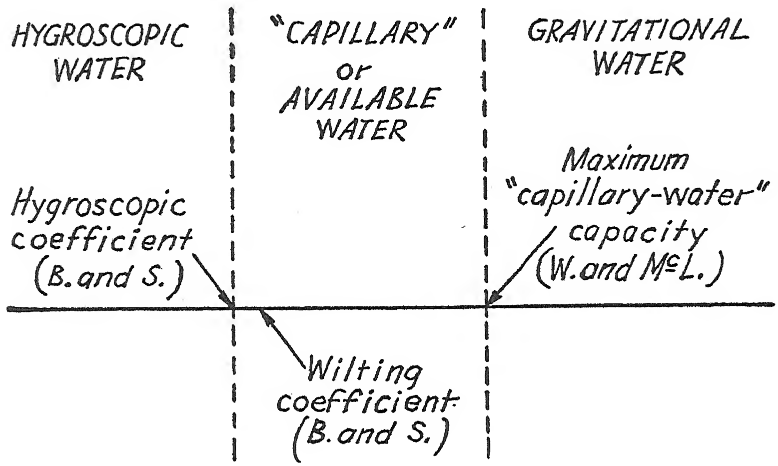

Fig. 4. Relation between wilting coefficient, hygroscopic coefficient, maximum capillary-water capacity, and the three divisions of soil water described by Briggs.

express the true dividing point between hygroscopic and available forms of water. (Fig. 4.)

The term "hygroscopic coefficient" means the quantity of water that a dry soil material will take up when it comes into equilibrium with an atmosphere saturated with water vapor at 75° F. To Briggs and Shantz this seemed to express the right dividing point between hygroscopic and capillary forms of water, and to provide a means for its measurement. Subsequent investigations, however, indicate that the three divisions of soil moisture suggested by Briggs are too broad. Alway (1913) and Shull (1916), for example, have shown that the wilting coefficient depends not only on soil-water relations, but on physiological functions of plants and on atmospheric conditions as well. Another factor involved is the action of plant roots in soils under natural field conditions.

The work of Puri, Crowther, and Keen (Eng., 1925) has shown "that the 'hygroscopic coefficient' has no real existence." In recent years the whole problem of soil water has become unsettled. However, the division names of "gravitational," "capillary," and "hygroscopic" are used as convenient descriptive terms.

Gravitational v. capillary water. A soil saturated with water is a poor medium for most crop plants, because saturation water not only shuts out air but also retards or stops the activities of helpful soil micro-organisms. For most crops, capillary water is the most important form, and crops draw heavily upon it for their needs. Some crops, however, like paddy rice, cranberries, marsh plants, low-land blueberries, and sweetclovers are particularly adaptable to saturated or wet soils.

Field moisture capacity. The maximum quantity of water a soil can retain against the force of gravity under field conditions, or the quantity held after excess mobile water has drained away, as shortly after irrigation or an effective rain, is called *field moisture capacity*, or *normal field capacity*. This includes capillary, hygroscopic, and bound waters. In general, the difference between the point of field moisture capacity and the point at which plants permanently wilt represents the greatest quantity of water a soil can hold for plant use at any moment.

How soils retain water. There are three principal forces concerned in the retention of water by soils; these are: (1) adsorptive force, which holds the water films around the soil particles; (2) capillarity, which accounts for the water in the pore spaces and particularly in the narrow interstices in soil crumbs or compound particles; and (3) the absorptive force created by the organic matter and colloidal materials in soils. The maximum quantity of water that a soil can retain is determined largely by its content of organic and inorganic colloidal matter.

Capacity of soils for retaining water. Obviously, a coarse sand can retain only a comparatively small quantity of water against gravity, whereas a deep, black silt loam or a dark-colored clay loam, rich in organic matter, can retain a comparatively large quantity. On the basis of unit weight, however, peat can retain more water than any other kind of soil material. A soil can retain a large quantity of water when it is fine-textured, contains a high percentage of colloidal matter, and is rich in organic matter, as may be shown by the following data:

QUANTITY OF WATER THAT SOIL MATERIALS CAN RETAIN [3]

Kind of Soil (Topsoil Material)	Total "Capillary" and Hygroscopic Water	Equivalent Quantity Held by Soil Material to Depth of 1 Foot	Approximate Maximum Quantity of Available or "Capillary" Water to Depth of 1 Foot
	Percent *	*Inches*	*Inches*
Coarse sand	15	3.2	3.0
Fine sand	22	4.2	3.6
Light-colored silt loam	30	4.4	2.6
Black silt loam	45	6.0	4.0
Peat in an advanced stage of decomposition	134	10.2	6.8

* Percent is based on the dry weight of soil material.

It would seem from the figures in the last column of the above table that coarse and fine sands would prove to be better sources of water for crops than a light-colored silt loam, for example. According to practical experience, however, sand gives up its water rather easily and completely, whereas a heavy silt loam or a clay soil holds water tenaciously, especially after the easily available supply is used up. Moreover, movement of water within the narrow interstices of compound particles may be very slow. This condition retards the rate of water absorption by plants roots. A light-colored silt loam, therefore, may be supplying a crop with sufficient water, while a sandy soil near by may have had its supply exhausted, as indicated by the wilting of the plants.

Droughty soils. The high sand content of some soils is the cause of their inability to support crops or carry them to maturity, for want of water. The topsoils of some sedimentary soils are sometimes very deceiving as to their agricultural value, owing to the fact that gravel or coarse sand, which has very low water-retaining power, occurs at a comparatively shallow depth. One should always consider the nature of subsoils in evaluating lands for agricultural purposes.

Soil materials v. soils. Much of our knowledge of soil water has been gained through the investigation of soil materials in physical laboratories. In the field, however, the physical nature or mechanical composition of subsoils may be a very important factor that affects the ability of the topsoils to retain water. Accordingly, the fundamentals regarding soil-water relations should be based

[3] WEIR, W. W. Productive Soils, p. 98. 1920.

on knowledge gained through the investigation of soils in their natural positions.

Movements of water in soils. The principal movements of water in soils are *infiltration, percolation, seepage,* tube *capillarity,* and movement due to suction-pressure. These movements concern gravitational and so-called capillary water. With the exception of seepage, the direction of water movements in soils is mostly vertical.

Infiltration. In soil studies that pertain to water conservation and watershed protection, *infiltration* means the filtering of rain water or artificially applied water into the ground or through the zone of aëration, with more or less absorption of that water in the zone of aëration (see Ch. 25).

Percolation. *Percolation* is the downward flow of gravitational water in the zone of aëration, or the flow of free ground water through earth interstices. In heavy or clayey soils, the rate of this flow is determined more by passageways like root channels, worm burrows, and structural cleavage than by the character or volume of the pore space of the soil mass. When clay swells and soil cracks close up, the rate of percolation slows up. Ordinarily, soil drainage depends on percolation.

Attention is called to the fact that percolation is one of the ways whereby water may be lost from some soils; other losses may occur through surface run-off, evaporation, and transpiration. Also, in some instances percolation impoverishes a soil.

Percentage percolation of rain water. The quantity of precipitation water that may percolate through soils depends on surface relief, openness of the soils, frost, vegetation or crop growth, and character of the precipitation. Under level and uncropped conditions at Rothamsted, England, practically 50 percent of the water of a 29-inch annual precipitation percolated through the soil.[4]

At Geneva, N. Y., with an average annual precipitation of 35.4 inches, 40.4 percent of the water percolated through an uncropped loam material placed in lysimeters, and 25.7 percent passed through the same soil material when it was cropped. Through loam material that represented another soil, about 44 percent of the precipitation water percolated when it was uncropped, and 19.2 percent when it was cropped.[5] Results of 15-year lysimeter experiments at Ithaca, N. Y., show a percolation loss of about 66 per-

4 The Book of Rothamsted Experiments, p. 23. 1905.
5 New York State Agr. Expt. Sta. Tech. Bull. 166. 1930.

cent of an annual rainfall of 32.5 inches through uncropped silty-clay-loam material, and a loss of about 50 percent through the same kind of material when cropped.[6] With an average rainfall of 49.3 inches at Knoxville, Tenn., lysimeter results show a loss of 50.7 percent of the rain water by percolation through an uncropped clay-loam material, and a loss of 47.3 percent through uncropped silt-loam.[7] However, surface run-off is the greater problem.

Crops lessen loss of water by percolation. At Ithaca, N. Y., the 15-year lysimeter tests showed that the cropping of a silty-clay-loam material had reduced the percolation loss of rain water 27.5 percent, which is equivalent to nearly 6 inches of rainfall per year. At Geneva, cropping lessened the percolation loss of water 36.4 percent on one loam and 56.3 percent on another.

Seepage. *Seepage* is the slow lateral movement of gravity water in the ground. *Effluent seepage* is diffuse discharge of ground water, as from a zone of saturation to the ground surface. *Influent seepage* is seepage into the ground. Also, *seepage* is water that slowly disappears into the ground from canals and reservoirs, and water that slowly appears at the ground surface. Effluent seepage is common in swamps. Capillarity may cause seepage from some canals. Wet zones on or at the foot of slopes may be due to seepage.

Capillarity. The term "capillarity" means "the action by which the surface of a liquid, where it is in contact with a solid (as in a capillary tube), is elevated or depressed."

To early soil investigators, the porosity of soil material suggested a bundle of capillary tubes. To these investigators, the problem of capillary movement of water in soils seemed a simple one, and extensive research pertaining to "capillarity" in soils was carried on along unscientific lines, because their hypotheses were not based on fact. King (1898) and Slichter (1898) made classical contributions to soil physics when they dealt with the flow of ground water, and assumed that the pore spaces of the earth materials involved were full of water. These and other investigators did considerable work in laboratories in determining "capillary" rise of water in columns of soil materials. The results obtained by Loughridge (1892), shown in the following table, are typical of their findings.

6 Cornell University Agr. Expt. Sta. Memoir 134. 1930.
7 University of Tennessee Agr. Expt. Sta. Bull. 138. 1927.

"CAPILLARITY" IN COLUMNS OF SOIL MATERIALS

CHARACTER OF SOIL MATERIAL	LENGTH OF TIME AND RISE OF WATER								
	1 Hour	6 Hours	24 Hours	2 Days	6 Days	12 Days	26 Days	125 Days	195 Days
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Sandy.......	8.0	12.5	14.0	15.0	16.5	—	—	—	—
Alluvial......	9.5	19	27	30.5	35	38	41.0	47	—
Silty........	2	9	13	17	20.5	25	31.5	41	50
Adobe.......	1.5	6	10.5	14.5	—	23	26.5	—	46

It is to be noted that water rose in the silty material to a height of 31.5 inches in 26 days, and to a height of 41 inches in 125 days. In this material it required 99 days for the water to rise from 31.5 to 41 inches, or 9.5 inches.

King concluded that water would rise in silt-loam soils from a depth of 10 feet in 45 weeks. McGee (1913) concluded that in the Great Plains region of Central United States, ground water could rise by capillarity as high as 10 feet a year, and under favorable conditions, as high as 30 or 35 feet in the course of several years.

Capillarity overemphasized. Early investigators thought that rain water that had penetrated deeply into the ground 4, 6, 10, and more feet below the root zone could return to the surface by capillarity and hence become available to field crops. Reasoning based on field observations, however, has led to quite different conclusions, and research has proved quite the contrary.

In a humid region, a drought seldom lasts longer than 6 weeks. During this length of time, according to the "capillarity" data given, water can rise in silt-loam and alluvial soil materials to heights of only about 33 and 42 inches, respectively. Hence, if the water supply on the surface is not renewed for a period of about 6 weeks, soil water probably will not rise from a greater depth than 3 or 3½ feet immediately below the roots. Capillarity, therefore, can be effective in only a limited way in supplying crops with water during a prolonged drought.[8] Most crop plants, particularly the succulent ones, cannot "wait" very long for "capillary" water; desert and semidesert plants, on the other hand, seem to have remarkable endurance in waiting for capillary water to move to their roots by exuding sufficient water to maintain "film-contact" between roots and soil particles.

[8] WEIR, W. W. Productive Soils, p. 96. 1920.

Capillary-tube hypothesis inadequate. Keen (Eng., 1928) has found that at a height of about 3 feet in a soil column capillarity is practically negligible. He has concluded that a depth about 3 feet lower than plant roots represents the ground zone from which a crop may obtain its water. He has pointed out also that the new parts of roots growing toward available water at a lower depth in a soil lessens the effects of capillarity in supplying plants with water.

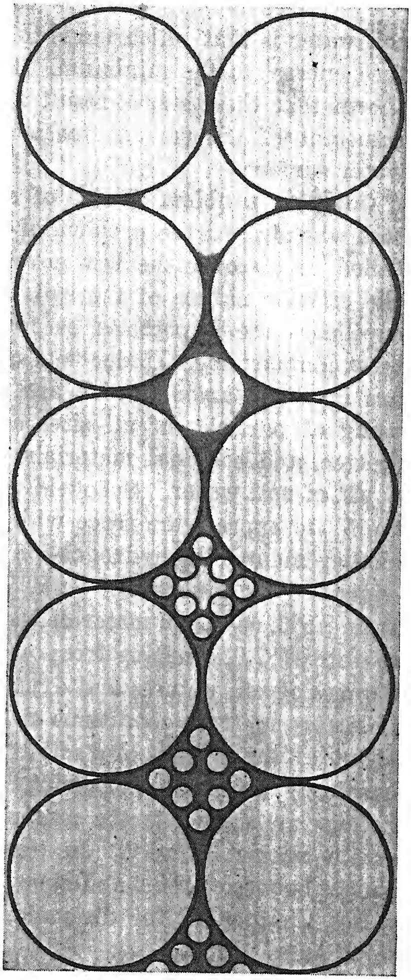

Fig. 5. Vertical equilibrium distribution of soil water from ground-water level up, in four stages: (1) water of complete saturation; (2) water that saturates only the small interstices and partly fills some of the larger pore spaces; (3) funicular stage; and (4) pendular stage in equilibrium with the vapor phase in the soil atmosphere.

The results previously discussed have shown that capillarity in soils not only has limitations, but also that the "capillary-tube" hypothesis has been found wanting, even in explaining the rise of water in columns of soil materials.

Equilibrium distribution of soil water. Keen (1924) has shown that the water retained in a soil column is either in a rising or a falling stage of equilibrium, depending on external conditions. He has inferred that in the "vertical equilibrium distribution," the soil water from the ground-water level up occurs in the following stages: (1) water that fills all the pore spaces; (2) water that fills only the small interstices and partly fills some of the larger pore spaces; (3) funicular stage; and (4) at the upper part of the soil column, the pendular stage which represents the water wedges

around the contact points of soil particles. The fourth stage is in equilibrium with the water vapor contained in the soil air (Fig. 5).

The force involved in this vertical equilibrium distribution of soil water is that which tends to reduce free water surface or surface energy to the minimum. Haines (Malaya, F. S., 1927) has shown that these stages result from *suction-pressure* which is the resultant of the surface tension and the total curvature of the water surface.

Complex problem of rise of soil water. The earlier investigators who studied the problem of the rise of water in a soil column failed to discover the law governing it, because they overlooked the cellular nature of the soil pore space, and they accepted the capillary-tube hypothesis as fact. The problem, however, is a most complex one. Under field or natural conditions, many factors are involved, among which are topsoil-subsoil relations, intermingling of particles of all sizes and shapes, soil structure, organic matter, and colloidal materials.

pF of soil water. Schofield (Eng., 1939) suggested the symbol "pF" to express the force with which water is held in soils, in a similar manner as hydrogen-ion concentration, or soil reaction, is expressed by the symbol "pH" (see index). Such values range from pF 0, as in soil material 1 centimeter above a free-water table, to near pF 7.0, resulting from oven drying. Hence, pF may express degrees of soil wetness and dryness. Accordingly, pF of about 3.2 indicates moisture conditions at field moisture capacity, and pF of about 4.2 the dryness of a soil at the permanent-wilting point. Accordingly, a pF value of about 3.0 of a soil is of great importance, because it represents the maximum quantity of water a soil can retain against gravity. In terms of pF, available soil moisture ranges between pF 3.2 and about pF 4.0.

See Chapter 12 for discussion of soil water in relation to soil fertility.

SOIL AIR

Inasmuch as soils are porous bodies, they contain air, which in an ordinary moist soil constitutes about 20 or 25 percent by volume. This air is either in direct contact with roots and soil micro-organisms or it is separated from them by a thin film of moisture or colloidal matter. Exchange of soil air takes place continuously, owing to changes in atmospheric pressure, temperature, moisture, and wind.

See Chapter 14 for discussion of soil aëration as a fertility factor.

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REVIEW QUESTIONS

1. What are first steps in soil study? With respect to multiformity of nature, how is thought simplified?
2. Describe the physical make-up of soils.
3. Describe the rock fragments that may occur in soils.
4. What are soil colloids? Their importance?
5. Discuss the physical relationships between soils and crops.
6. Describe the difference between soil organic matter and humus.
7. What are some basic concepts regarding soil water? Illustrate.
8. Discuss the arbitrary divisions of soil water.
9. Define moisture equivalent, wilting coefficient, hygroscopic coefficient.
10. Define soil moisture and field moisture capacity; relation to plants.
11. Describe the movements of water in soils.
12. Discuss capillary rise of water in soils.
13. Discuss the factors of water retention by soils; soil capacity.
14. What is meant by soil pF values?
15. Express the range of available soil moisture in terms of pF.

CHAPTER 3

PHYSICAL PROPERTIES OF SOILS

The first definitely scientific study of physical soil properties was made by Schübler (Ger.) in 1838, although work of less scientific importance was done by Davy (Eng.) in 1813. Including results of certain simple chemical analyses, Schübler correlated the physical properties, and thereby gave significance to some of the commonly known soil facts—about clays, sands, and droughty soils, for example. But this early development of soil physics was arrested for a time, owing to the great discoveries made in soil and plant chemistry soon after these scientific studies were begun.

About the time when systematic study of physical soil properties began, remarkable advances were made by Boussingault, Liebig, and Lawes and Gilbert in chemical inquiry into problems of plant nutrition, and physical soil studies were forced into the background. It seemed then that the secret of soil fertility was to be found solely within the realm of chemistry. However, after 50 years of outstanding achievements in agricultural chemistry, a revival of interest in physical soil properties in relation to plant growth began, when in 1878, Wollny (Ger.) started publication of investigations pertaining to agricultural physics.

Soil physics. The work of Wollny and that of Hilgard (1833-1916), King (1889-1895), and others established the basis of a new agricultural science, namely, soil physics. In this field of science the following principal soil properties are recognized: weight, texture, cohesion, consistence, structure, porosity, absorption, adsorption, color, temperature, and tilth. These properties are discussed in the order named.

WEIGHT, ABSOLUTE AND RELATIVE

By weight, sand is the heaviest soil material. In round numbers, an acre of it about 7 inches deep weighs 2,500,000 pounds; silt-loam or clay-loam material to the same depth weighs 2,000,000 pounds; muck, 1,000,000; and light peat, 500,000 pounds. A cubic

foot of dry sand weighs about 106 pounds; the same quantity of silt-loam material, about 90 pounds; and light peat, about 22 pounds.

Specific gravity. The specific gravity of a solid substance has been defined as the ratio of the weight of that substance to the weight of an equal volume of pure water. The following figures show the specific gravity of some rock-forming minerals: quartz, 2.65; orthoclase, 2.56; dolomite, 2.85; limonite, from 3.6 to 4; kaolinite (kaolin), 2.5; muscovite (white mica), from 2.7 to 3; and hematite, from 4.5 to 5.3. The specific gravity of ordinary mineral soil material varies from about 2.2 to 3.3.

Apparent specific gravity. Inasmuch as specific gravity of soil materials excludes the pore spaces, *apparent specific gravity* is of greater importance than specific gravity. Apparent specific gravity is the relative weight of water-free soil material (with pore spaces), obtained by dividing the weight of a unit volume of dry material by the weight of an equal volume of water under standard conditions. The apparent specific gravity of sand is 1.7; of silt-loam or clay-loam material, about 1.4; and of light peat, about 0.34.

Although the specific gravity of quartz sand is practically the same as that of the other mineral soil particles, a wagon load of ordinary silt-loam material is considerably lighter in weight than an equal-volume load of sand, because there are more open spaces in the load of the finer material. With fewer open spaces, a load of dry sand, volume for volume, is heavier than a shoveled-on load of moist fine sand containing about as much as 5 percent water. Bulking of the wet sand is due to the films of water around the soil grains, which prevent the particles from coming in close contact, as in dry sand.

SOIL TEXTURE

The term "texture" refers to the qualities of coarseness and fineness. Soil texture may be defined as *that quality of mineral soil material which results from its proportional composition of sand, silt, and clay.*

Soil texture. Mechanical composition, which has been generally accepted as the basis of soil texture, enables one to express this quality in simple mathematical terms. In harmony with the meaning of soil texture, soil investigators in the United States have

defined the limits of the principal soil textures according to mechanical composition as follows:

PRINCIPAL SOIL TEXTURES
(Named in Order According to Clay Content)

Texture	Limit in Percentages of Soil Separates		
	Sand	Silt	Clay
	Percent	*Percent*	*Percent*
Coarse sand	80 to 100 *	Less than 15 percent silt and clay	
Fine sand	80 to 100 †	Less than 15 percent silt and clay	
Loamy sand	70 to 100 ‡	From 15 to 20 percent silt and clay	
Sandy loam	50 to 80	0 to 50	Less than 20
Loam	30 to 50	30 to 50	Less than 20
Silt loam	0 to 50	50 to 100	Less than 20
Sandy clay loam	50 to 80	0 to 30	20 to 30
Clay loam	20 to 50	20 to 50	20 to 30
Silty clay loam	0 to 30	50 to 80	20 to 30
Sandy clay	50 to 70	0 to 20	30 to 50
Silty clay	0 to 20	50 to 70	30 to 50
Clay	0 to 50	0 to 50	30 to 100

* Including fine gravel.
† Containing 50 percent or more fine sand and very fine sand.
‡ Containing 35 percent or more fine gravel.

Textural qualities of soils, as listed above, may be modified by rock fragments or stones, for example, granular desert soil (young soil formed through disintegration of granites), gravelly loam (30 or more percent gravel by vol.), and stony sand (rather large number of stones). (See pp. 28 and 132.)

It is to be noted that there is no silt texture to correspond with that of the sands, for the reason that no soil materials have been found that contain such great percentages of silt as sandy materials have of sand. A soil material composed almost entirely of silt is less likely to be found than one that consists entirely of sand particles. So far as the United States is concerned, soil materials that are composed entirely of clay are unknown. Some soil materials in tropical regions analyze nearly 100 percent clay.

Importance of texture. As a rule, fine-textured soils, such as silt loams and clay loams, have higher agricultural value than those of coarse texture. By nature, the former are usually comparatively well supplied with nutrient elements, and they have the ability to retain water; whereas the latter are commonly open, poor, and more or less droughty. Most soils in the United States have silt-loam texture. A smaller number are loams, and then follow the fine sandy loams.

Texture and organic matter. Commonly the coarse-textured soils are easier to till than those of fine texture. For this reason such soils are often called "light" and "heavy," respectively. In places the "heaviness" of a soil, as the clay content of its topsoil material would indicate, is completely masked by organic matter, so that an apparently heavy soil may be not only more easily worked, but also more productive than another soil of similar mechanical composition.

SOIL COHESION

The comparatively low cohesion of moist, coarse sand is due to water films. There is greater cohesion in moist fine-textured materials, owing to the combined effect of water films, the binding action of organic matter, and the physical forces that are associated with colloidal matter. Measurements of the cohesive force of ultra-clay, for example, may be determined by the *crushing strengths of briquets.* The test briquets are made of standard sand in which are mixed certain quantities of the material to be tested, and they are compared with briquets that contain equal quantities of portland cement. Ultra-clays may show crushing strengths many times greater than those of standard cements.

In the field, a heavy clay, on drying, may shrink and form very hard chunks or clods (Fig. 6). But the clay does not "set" as does cement, for on the addition of water, it resumes its normal condition.

SOIL CONSISTENCE

Cohesiveness of soil materials has given rise to a number of attributes which are grouped under the general term "consistence" which means the state of soil material adhering together *en masse,* as measured by resistance to separation or deformation. These qualities may be described, for example, as *plastic, sticky, friable, mellow, crumby, compact, loose* or *open, soft, firm, hard,* or *cemented.*

In his investigations of cohesion of soil materials, Atterberg (Swed., 1911-1912) has suggested the *plasticity coefficient,* or the percentage of water in clay at the point when it ceases to be plastic and becomes viscous, as the basis for expressing soil plasticity. In his studies, he measured cohesive force in terms of the force required to rupture prisms of soil materials by placing them between a steel wedge and a sharp plunger. He made the prisms by

first wetting soil materials to the plastic condition and then drying them to different water contents.

Plasticity means the degree to which a given quantity of moist soil material can be deformed without rupture.

Shrinkage of soils. Commonly, when the water of a heavy soil is reduced to a low percentage, cracks form as the result of shrink-

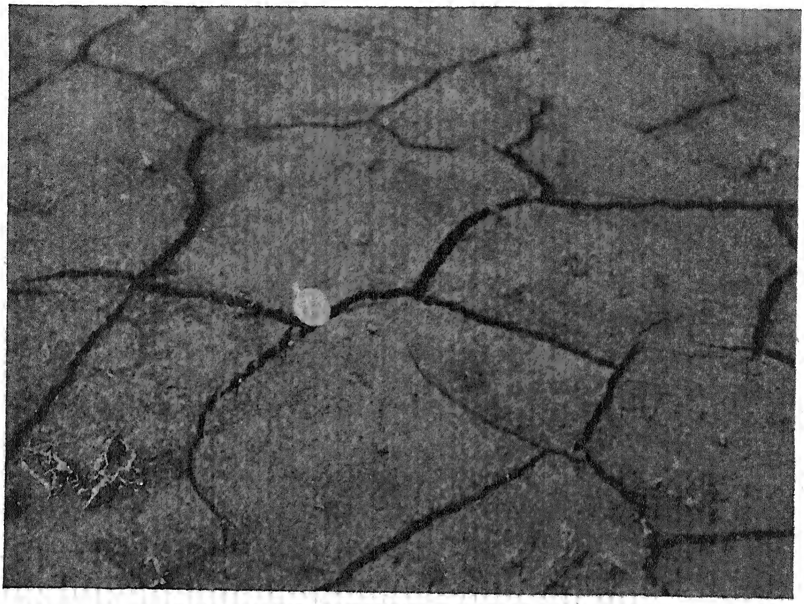

Fig. 6. Soil shrinkage. Through cohesion, clayey soil material, on drying, draws together into compact masses, resulting in decrease of volume and development of cracks. The watch shows size of cracks.

age. Through cohesion, the soil material draws together into compact masses, resulting in a decrease of soil volume and development of checks and wide cracks (Fig. 6). When such a dry, cracked soil is wetted, the soil material swells, resulting in an increase of soil volume and disappearance of the cracks, if sufficient water is applied.

The cause of shrinkage and swelling centers in the colloidal materials, both mineral and organic, of which shrinkage and swelling are dominant properties. In his study of the irrigated lands of the Nile Valley, Mosseri (Fr., 1923) has observed that the process of shrinking and cracking of the heavy, deposited materials pro-

duces two favorable results: it improves tractability of the land and affords a means for the removal of alkali salts.

SOIL STRUCTURE

Under natural conditions, individual soil grains, except in sands, become grouped into compound particles, forming macroscopic aggregates. Important operative factors include soil organic matter,

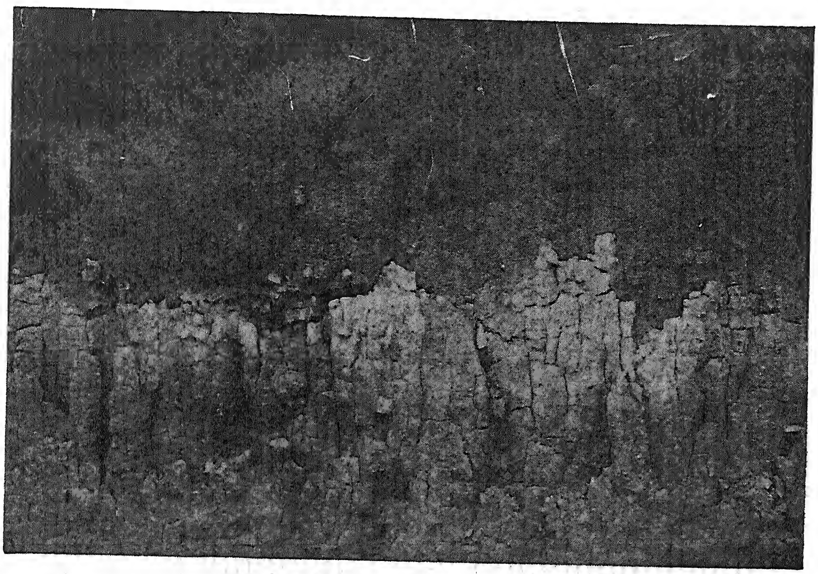

Fig. 7. Prismatic soil structure.

cementing substances, colloidal materials, and the effects of water and of substances formed by soil micro-organisms. Hence, soil structure implies the natural arrangement of soil particles, which arrangement may be described, for example, as *single grain* (as in sands), *massive, laminate, platy, crumby* (Fig. 25, II and III), *cloddy, prismatic* (Fig. 7), *columnar* or *pillared* (Fig. 8, B), *granular, lumpy, cubical,* or *nodular* (Fig. 8, A).

Puddling. Soil structure is of the greatest practical importance in the development and maintenance of a physical soil condition that favors plant growth. Through poor soil management, structure may be destroyed. When heavy soil materials are plastic, owing to the presence of considerable water, it is easy to destroy natural structure by massing fine-textured materials either through

pressure or the use of certain fertilizing chemicals, thus creating a *puddled* condition. In farming this can happen when heavy loads are drawn over wet fields and when land is plowed too wet. On drying, a puddled soil or soil material becomes very hard and compact. Hence the term "puddled soil."

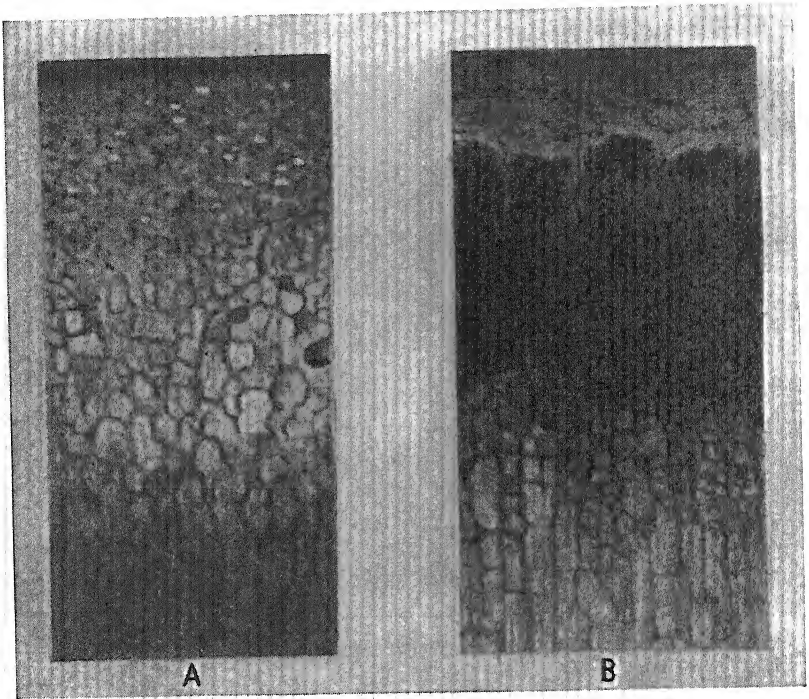

Fig. 8. Soil structures: A, gray nodular soil; B, black pillared alkali soil. (After Vilensky, Russ., 1925.)

Granulation. Alternate wetting and drying or alternate freezing and thawing of soils will correct a puddled condition. According to Bouyoucos (1924), the principal agent in granulation is water. It does not act by pulling the soil particles together, but rather by pushing them apart, thus causing the clods or the dense masses to crumble. Ultimately granules or crumbs develop. In this process, water does two things: it causes swelling of the colloidal materials, and it diminishes the cohesive force by coming in between the particles and forcing them apart.

Freezing may aid in effecting granulation of puddled soil ma-

terials, also plowing shortly after an effective shower. Ice crystals force soil particles apart, and may completely break cohesion, thus tending to form soil crumbs separated from each other by layers of ice. On the other hand, thawing when accompanied by heavy rains may have a destructive effect on soil structure.

SOIL POROSITY

Soils are very porous bodies. About 40 percent of the volume of dry, compact sand and about 60 percent of dry, compact muck is air. By volume, about one half of the most common soils—silt loams, loams, and fine sandy loams—consist of pore spaces which are of cellular nature. Under moisture conditions for optimum plant growth, about 20 percent of a given volume of fine sandy loam, silt loam, or clay loam consists of pore spaces.

Importance of porosity. Porosity enables soils to supply roots with water, and at the same time provide aëration. Moreover, soil porosity is important in biological activities, exchange of CO_2 and O, chemical reaction, important biochemical changes in plant nutrition, and makes possible infiltration (see p. 36).

SOIL ABSORPTION

Soils are absorbent bodies, both physically and chemically. Absorption is probably one of the oldest-known soil properties, for primitive husbandmen soon learned that crop production depended on the ability of the earth to absorb water. The importance of this property in relation to water has been discussed in Chapter 2. Absorption concerns both colloidal clay and humus.

Like most other material bodies, soils absorb heat and radiant energy. This is discussed under "soil temperature" in subsequent paragraphs.

Another type of absorption has been known since 1850: namely, the absorbent action of soils with reference to soluble salts. As this is a chemical property, it is discussed in Chapter 4.

SOIL ADSORPTION

The term "adsorption" has been defined as the concentration, at the point of contact, of vapors, gases, and dissolved substances on the surfaces of solid bodies. In a soil, the principal adsorptive bodies include colloidal clay and humus. Anderson (1922) has shown that the adsorptive power of a soil for certain substances is due

largely to colloidal materials. Adsorption in soils concerns water vapor principally, and ions and certain gases also.

Soil colloids differ in their adsorptive powers, probably owing to the fact that they differ in kind. Middleton (1926), working with colloids from 8 widely different soils, found that they adsorbed from 0.0518 to 0.1776 gram of water to 1 gram of colloid, in an evacuated desiccator over 30 percent sulphuric acid at 30° C. He also found that they adsorbed more moisture than ammonia, indicating, he suggested, that adsorption is in accord with the capillary theory, or that the mechanism involved is similar to the adsorption of gases by charcoal and silica gel. On the other hand, Wilsdon (India, 1921) has advanced the view that colloids are reticular or porous in nature, and that the water that they contain not only fills the minute cell-like cavities, but is also adsorbed in the walls of the gel. On the basis of this hypothesis, Hardy (Trinidad, 1923) explained the shrinkage of certain lateritic soils.

It is probable that adsorption of water vapor is a most important factor in aiding the rise of water in a column of dry soil material.

SOIL COLOR

Color, one of the most common attributes of soils, varies widely, from almost pure white to black, depending principally on the kind of material, quantity of organic matter and humus, degree or stage of oxidation, and the presence of coloring substances like iron oxides and manganese.

Ferric oxide (Fe_2O_3), like hematite, gives a red color to soils—to those of the Piedmont Plateau, for example. Hydrated ferric oxide ($2Fe_2O_3{\cdot}3H_2O$), like limonite, on the other hand, imparts a yellow color, as in the yellow soils of the southern States. Manganese, when present in greater or lesser quantities, makes soil materials black or produces shades of colors. The black color of some sands is due primarily to manganese.

Soil colors. Under the usual dark-colored humus layers of virgin soils, a large number of different-colored layers may be found. A single soil may have two or more such layers. A list of colors, based on natural soil materials, has been made by the United States Soil Survey. These should give some idea of what one might expect to find regarding different-colored layers in soils. This list comprises the following colors, including tints and shades: white, grayish white, light gray, gray, dark gray, cream color, light gray-

ish yellow, yellow, yellowish brown, brown, light reddish brown, reddish brown, dark brown, dark grayish brown, very dark brown, very dark grayish brown, black, olive gray, dark olive gray, mouse gray, yellow olive, dark olive drab, light reddish yellow, yellowish red, red, deep red, dark red, dark brownish red, purplish brown, grayish purple, and purplish red.

Importance of color. Considerable significance has always been attached to soil colors, particularly in their relation to productivity. In soil classification and pure soil science (pedology), color is a most important distinguishing characteristic. It was color more than any other attribute that directed the attention of the Russian soil scientists to a consideration of soils as a subject for scientific inquiry. Soil colors, however, are not fixed. In soil development and under cultivation, especially, they undergo many changes. For example, cropped soils lose much of their organic matter, and as a result become lighter in color. This is one of the reasons why any soil classification based on color alone is not sound, nor scientific; all distinguishing features must be considered.

SOIL TEMPERATURE

Generally, soil temperature rises and falls daily, as in diurnal waves whose amplitudes increase from winter to summer and decrease from summer to winter. A closer study of soil-temperature curves will show that there are two principal kinds of temperature waves—daily and seasonal—the one being superimposed upon the other. Each of these waves represents an ebb and flow of heat.

The temperature of a soil represents the balance between heat received by it and lost from it. A soil receives heat in four principal ways: (1) by direct radiation from the sun; (2) from warm rain water; (3) by conduction from the interior of the earth; and (4) from biochemical, chemical, and physical changes that take place within it. And, conversely, a soil loses heat in three principal ways: (1) by radiation; (2) by conduction to cooler strata below and to cooler air above; and (3) through evaporation of soil water.

Other factors that affect temperature. There are several other important factors that affect soil temperature; these are latitude, topographic relief, altitude, proportionate distribution of land and water, air and water currents, vegetation and other covers, soil water, and kind of soil. Each of these factors will be briefly discussed.

Latitude and topographic relief concern not only distribution of radiant energy per unit area, but also loss of solar radiation by reflection. For example, 1 square mile of the sun's rays fall perpendicularly on 1 square-mile area; but obliquely, they may fall on an area of 1.4 square miles. Moreover, loss of radiant energy by reflection is greater than when they fall perpendicularly. This partly explains why, in the Northern Hemisphere, the soil temperature on a north slope may be lower than that on the opposite south slope. In some places horticulturists take advantage of this fact in selecting north slopes for favorable orchard sites. Furthermore, the different exposure of opposite mountain slopes, particularly in arid and semiarid regions, may affect the supply of available water in the soils sufficiently to cause the development of two different types of natural vegetation. Grasses may be found on the slope where the greater loss of water takes place, owing to higher temperature from the direct sun's rays; while chaparral may develop on the opposite slope, where evaporation is not so great.

Altitudinal differences in soil temperature may be explained by the fact that the temperature of the atmospheric blanket generally lowers with higher elevation above sea level, diminishing at an average rate of 1° C. to 550 feet.

Distribution of land and water bears an important relation to climate, in that large bodies of water tend to equalize atmospheric temperature. This modifying effect of water on climate is, in turn, reflected in the average temperatures of the soils of the region involved.

Air and water currents, as is well known, profoundly affect the climate of certain regions, and directly and indirectly affect soil temperatures. On a given parallel in the middle latitudes, the temperature over the western coast of a continent is higher than that over its eastern coast, principally because prevailing westerly winds bring with them the warmer atmospheric conditions of the regions of their origin. The effects of the Gulf Stream on the climate of the British Isles and northern Europe are well known; also the effects of the cold Humboldt or Peruvian ocean current which flows from the Antarctic region along the west coast of South America.

Vegetation and other covers protect soils from exposure to the sun's rays, so that during summer the temperature of bare land is

higher than that of land covered with vegetation; for example, Li (1926), in New England, found that soils under cover of grasses and especially under forest litter were cooler in summer and warmer in winter than similar soils that were bare. Although vegetable growth like forest trees and grasses intercepts incident radiant energy, atmospheric movements tend to equalize the temperature of the air layer that is in immediate contact with the ground.

In regions that have freezing weather during winter, the beneficial protective action of mulches on flower beds, of snow on winter grains, and of cover crops or snow, or both, on clover and alfalfa seedlings, for example, may be explained on the basis of temperature relations. A very important effect of this cover is in lessening or preventing alternate freezing and thawing which is so harmful to crops, particularly during early spring. These protective covers act like poor conduction blankets, especially during sudden and extreme temperature changes. They reduce the loss of soil heat during very cold weather and reduce the conduction of atmospheric heat to the frozen ground during mild weather.

Water conducts heat slowly, yet moisture aids conduction of heat into soils by improving thermal contact between soil particles. A soil that contains its optimum quantity of moisture is also in best condition for warming up by conduction of heat from the surface. The opposite is true as regards the action of a dry earth mulch. Such a loose layer of soil material acts like a blanket in maintaining a more even soil temperature below it.

Saturated and poorly drained soils, on the other hand, are commonly called "cold" soils, owing to the fact that they warm up very slowly, so much more heat being required to raise the temperature of water than of soil material.

The kind of soil influences soil temperature principally by reasons of color and texture. Under like conditions, black soils warm more quickly than do light-colored soils, owing largely to the capacity of black materials for absorbing heat. It is common knowledge that sandy soils are "early" or "warm" soils, largely because they are open and do not contain so much water as do heavy soils.

Heat of wetting. Mention should be made of a phenomenon called "heat of wetting" which is the evolution of heat from hygroscopic substances when they are moistened. In soils, this phenomenon occurs in connection with the fine soil materials, especially the colloids, so that the quantity of heat evolved on wetting

soil materials increases with fineness. This is typically shown in the following data published by Müntz and Gaudechon (Ger., 1909):

HEAT OF WETTING IN RELATION TO FINENESS OF SOIL PARTICLES

Soil Separate	Percentage of Separate Present in Soil Material	Heat Evolved from 1 Gram of Separate
	Percent	*Calories*
Coarse sand (>0.1 mm)	11.30	0.00
Fine sand (0.1 to 0.05 mm)	16.52	0.26
Sandy silt (0.05 to 0.01 mm)	44.89	0.64
Clay silt (<0.01 mm)	27.29	3.10

Colloidal soil materials give comparatively high heats of wetting, though varying according to kind of material. Anderson and co-workers (1922) and Bouyoucos (1925) have established the fact that soil collpids differ in regard to heat of wetting, and accordingly have suggested a basis for their differentiation. Anderson and Mattson (1926), working with colloids extracted from eight widely different soils, found that heat of wetting varied from 5.3 to 17.5 calories per gram, increasing according to the number of particles in 1 gram of material. Results of these investigations indicate that when a dry soil becomes wetted, as with rain water, a certain amount of heat is generated.

Importance of soil temperature. The importance of soil temperature in relation to production of food crops is discussed in Chapters 9 and 23.

TILTH

The meaning of the term "tilth" is based on the relationship between physical soil conditions and seed germination and plant growth. In general, it is the state of being tilled or cultivated. The term "poor tilth" may be defined as that physical condition which is not favorable to seed germination and plant growth, whereas good tilth means a physical condition that is favorable.

Tilth is an important factor that determines depth of planting, contact between seeds and soil material, contact between roots and soil particles, and penetration and development of roots. Thus, a soil the material of which is too loose, very hard, lumpy or cloddy, or too compact, may be described as having poor tilth. On the other hand, physical soil conditions that favor planting, germination of seeds, root development, and subsequent plant growth are implied in good tilth.

Factors that determine tilth. All the physical soil qualities or properties are embraced in tilth. Thus, tilth may be regarded as the practical aspect of the sum of all the physical attributes of a soil, or it may be regarded as the common contact point, as it were, between physical soil properties and crop production. The importance of good tilth in soil fertility is discussed in Chapter 11.

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REVIEW QUESTIONS

1. Is it possible to know what soils are, physically, except by their physical properties? Explain.
2. Name the principal physical attributes of soils.
3. What is the specific gravity of loam and silt-loam material? Explain why.
4. What is the difference between soil texture and structure? Illustrate.
5. Discuss the importance of soil texture.
6. Explain why soil cohesion is measured by the crushing strength of briquets.
7. What terms are used to describe soil consistence? Illustrate each.
8. When is a soil said to be puddled?
9. Discuss the importance of soil porosity.
10. Distinguish between soil absorption and adsorption.
11. What relationship is there between soil color and soil fertility?
12. Discuss the various factors that affect soil temperature. Give examples.
13. What is soil tilth? Discuss its importance.
14. Why will a small black or dark-colored object on ice apparently eat its way into the ice on a sunny day, even though the air temperature may be far below freezing? What bearing has this fact on soils?

CHAPTER 4

CHEMICAL NATURE OF SOILS

For many years following the establishment of scientific agriculture in 1840, soils were regarded simply as reservoirs of plant-food elements. According to this concept, the ability of soils to produce crops could be completely diagnosed through chemical analysis only. It is a singular fact that after 1802, for nearly 125 years, chemical analytical work dominated the greater part of soil investigations. Now it is generally recognized that soil fertility is determined, not by any restricted factor, but by the mutual interaction of physical, chemical, and biological forces. The chemical forces, although essential, are by no means the most important.

From the extensive analytical work that has been done and from modern chemical soil research, much valuable information about the chemical nature of soils has been gained—about mineral constituents, organic matter, soil solutions, soil air, soil reaction, and availability of the nutrient elements.

MINERAL CONSTITUENTS

Chemical composition of soils v. rocks. Inasmuch as soil-forming materials originate from rocks through weathering, one may conclude that, in general, the chemical composition of soils is similar to that of rock masses. Except for the fact that some rock elements suffer greater losses during weathering than others and that as a consequence the percentages of certain other elements increase relatively, the chemical composition of rocks and mineral soil materials are similar. This may be shown by the facts given in the accompanying table. The percentages given for the rock masses are weighted averages, involving igneous rocks, shales, sandstones, and limestones. The average percentages for the so-called "humid" soils represent 466 soils of southern United States; those of "arid" soils represent 313 soils of arid areas of western United States; and those of loess are the averages of 7 samples taken from as many parts of the United States.

AVERAGE CHEMICAL COMPOSITION OF ROCKS AND SOILS [1]

Ingredients, Expressed Mostly as Oxides	Rock Masses	"Humid" Soils	"Arid" Soils	Loess
	Percent	*Percent*	*Percent*	*Percent*
Insoluble in HCl	——	84.031	70.565	——
Soluble SiO_2	——	4.212	7.266	——
SiO_2, silica	59.08	——	——	67.11
Al_2O_3, alumina	15.23	4.296	7.888	11.76
Fe_2O_3, ferric oxide	3.10	3.131	5.752	3.36
FeO, ferrous oxide	3.72	——	——	0.56
MgO, magnesia	3.45	0.225	1.411	2.06
CaO, lime	5.10	0.108	1.362	4.09
Na_2O, "soda"	3.71	0.091	0.264	1.39
K_2O, "potash"	3.11	0.216	0.729	2.17
CO_2, carbon dioxide	0.35	Undet.	Undet.	2.97
S, sulphur	0.049	Undet.	Undet.	Undet.
SO_3, sulphur trioxide	0.026	0.052	0.041	0.114
P_2O_5, "phosphoric acid"	0.285	0.113	0.117	0.18
MnO, manganese oxide	0.118	0.133 (Mn_3O_4)	0.059 (Mn_3O_4)	0.036
Cu, Zn, Pb, copper, zinc, lead	0.016	Undet.	Undet.	Undet.
Other elements	1.316	Undet.	Undet.	0.056
Water	1.310	3.644	4.945	3.93
C, or organic matter	0.040(C)			0.076(C)

Mineral framework of soils. Owing to the fact that the coarse soil particles consist largely of unaltered or primary mineral particles, their chemical composition is similar to the rock-forming minerals. Chemically, these coarse particles are almost inactive, except as they serve as sources of nutrient elements when they undergo decomposition. But so far as immediate availability of elements for plant growth is concerned, they may be regarded, generally, as practically inert. They serve mainly in a mechanical capacity, as of support and framework.

Clay particles are different from any of the original rock minerals; they are products of chemical processes in rock weathering. Clays are regarded as salts or true chemical compounds of insoluble, complex, alumino-silicic acids. They are the colloidal materials, and constitute the active division of soil constituents, in that some of these complex compounds may contain calcium, magnesium, potassium, hydrogen, sodium, and other elements which can be partly displaced by salts, acids, and bases without breaking down or changing their form. This phenomenon, called "base-exchange," is discussed in subsequent paragraphs of this chapter.

[1] CLARKE, F. G. THE DATA OF GEOCHEMISTRY. Dept. Int. U. S. Geological Survey Bull. 770. 1924.

Chemical composition of soil separates. Failyer and co-workers (1908) have made numerous chemical determinations of soil constituents according to the principal fractions. From their results, the following data have been selected to show the comparative chemical composition of sand, silt, and clay, based on calcium, potassium, and phosphorus contents:

PERCENTAGES OF CALCIUM, POTASSIUM, AND PHOSPHORUS IN SAND, SILT, AND CLAY

Kinds of Soil Materials	Calcium as CaO			Potassium as K_2O			Phosphorus as P_2O_5		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
	Per-cent	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*
Residual from crystalline rocks.....	0.50	0.82	0.94	1.60	2.37	2.86	0.07	0.22	0.70
Residual from limestone	12.26	10.96	9.92	1.46	1.83	2.62	0.28	0.23	0.37
From the Coastal Plain.	0.07	0.19	0.55	0.37	1.33	1.62	0.03	0.10	0.34
Loess and glacial.......	1.28	1.30	2.69	1.72	2.30	3.07	0.15	0.23	0.86
From arid regions......	4.09	9.22	8.03	3.05	4.15	5.06	0.19	0.24	0.45

From the table we can see that, with the exception of the calcium or lime of the residual materials from limestone, the percentages of calcium, potassium, and phosphorus increase with fineness of particles. The table also explains in part why coarse-textured sands are poor soils, and why loams, silt loams, and clay loams are usually productive.

Chemical composition of soil colloids. Robinson and Holmes (1924) have made chemical determinations of colloidal materials of 30 widely different soils, excepting peat and laterites, from Puerto Rico and from 14 different States covering a wide area from California to New York and from Iowa and Nebraska to Texas.[2] The following conclusions may be drawn from their data:

1. Soil colloidal materials are composed principally of silica, alumina, combined water, iron oxide, organic matter, and smaller quantities of potassium, magnesium, calcium, sodium, phosphorus, manganese, sulphur, titanium, and chlorine, comparative quantities being indicated by the order named.

2. The percentages of silica range from 31.84 to 55.44, and those of alumina from 16.42 to 38.28. In most instances the percentages of silica and alumina vary inversely; when the quantity of silica is high, the total quantity of potassium, magnesium, calcium, and sodium is high, and when the percentage of silica is low, the total quantity of alkalies and alkaline earths is low.

[2] U. S. Dept. Agr. Dept. Bull. 1311. 1924.

3. Red and yellow colloidal soil materials showed the effect of leaching more profoundly than gray or black materials.
4. The proportions of alumina, silica, iron oxide, and combined water do not indicate that these constituents are present in soil colloidal materials in the form of common silicates like kaolinite and nontronite, although there may be some such minerals present.

ABSORPTION (CHEMICAL)

Chemical absorption by soil materials has been known since 1850, when Thompson (Eng.) showed quantitatively that when ammonium sulphate decomposed after being dissolved and thoroughly mixed into soil materials, ammonia was fixed, while calcium was driven into solution. During the same year, Way (Eng.) found that in the absorption, the quantity of calcium displaced was equivalent to that of the basic part of a salt. He also found (1852) that the active absorbent agent was contained in clay, and that only basic elements like calcium, magnesium, potassium, and sodium were concerned in this phenomenon and not elements of acid radicals, like nitrogen, phosphorus, and sulphur. He suggested that the inorganic materials concerned were aluminum silicates.

Since 1850 extensive inquiry into the problem of chemical soil absorption has been made. Ordinarily, this property concerns many of the chemical constituents of soils. When nitrate, sulphate, and chloride solutions are passed through soil materials, the basic elements are absorbed, whereas most of the acid parts come through in the filtrates. On the other hand, when the same basic elements are added as phosphates and silicates, both basic and acidic parts may be absorbed. Soils are chemically absorbent bodies by virtue of the fact that they consist of (1) inert chemical compounds; (2) difficultly and easily soluble substances; (3) soluble salts and acids; and (4) complex insoluble compounds that have the property of exchanging their basic elements for other basic elements and hydrogen. Inquiry into the latter compounds, now called base-exchange studies, has led to many important discoveries. Absorption and adsorption of ions, collectively, is called *sorption.*

Absorption hypotheses. Way (1850) explained soil absorption on the chemical basis; that is, calcium and ammonium (NH_4), for example, exchanged places according to chemical reaction. Liebig held the view that absorption was physical, like the absorption of gases by charcoal. Since 1861, when Graham (Eng.) introduced the term "colloids" and so shaped the concept regarding them as

to make possible scientific inquiry into their nature, absorption research in soil science has centered on colloidal soil materials. Van Bemmelen (Holl., 1878) was the first investigator to observe the colloidal properties of the clay and humus of soils. At first he accepted Way's chemical hypothesis of absorption, but later (1890) he concluded that displaceable basic elements were held in soils by *adsorption,* that is, on the surfaces of colloidal particles. The adsorption hypothesis was dominant up to about 1924, when substantial evidence to the contrary was discovered by European investigators.

Base-exchange in soils. It has already been pointed out that Way first investigated the exchange of basic elements in soil materials. Since the quantitative studies made by Gedroiz (U.S.S.R., 1924) and Hissink (Holl., 1925) regarding this property of soils, it has been called "base-exchange."

Two principal kinds of base-exchange compounds are present in soils—organic and inorganic. According to results of investigations, base-exchange may be defined as the displacement of basic elements (including hydrogen) that are chemically combined in insoluble soil compounds by other basic ions and hydrogen when soil materials are brought in contact with salt, base, and acid solutions. For example, a base-exchange compound containing sodium may have its sodium partly displaced by calcium in a solution of calcium chloride, while the sodium that is displaced goes into solution as sodium chloride. The sodium of the base-exchange complex is a displaceable "base," whereas the calcium of the solution is a displacing agent.

A basic element, when present in displaceable form in a base-exchange material, may be displaced by any one of the other basic elements, as sodium by calcium, calcium by sodium, potassium by calcium, and sodium by magnesium. Under certain conditions, the exchange may take place with great rapidity. Named in the order of their activity, according to Gedroiz, cations, or positive ions, of hydrogen (H^+), calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^+), ammonium (NH_4^+), and sodium (Na^+) may act as displacing agents (cations, see footnote, p. 68). Hydrogen ions are most readily absorbed and the hardest to displace. Calcium ions are about twice as effective as sodium in displacing hydrogen. Magnesium and potassium are readily displaced; calcium less so. Divalent cations of manganese and iron are also exchangeable.

Base-exchange illustrated. The principle of base-exchange may be simply illustrated in the use of synthetic exchange-silicates (zeolites), or permutites, in softening hard waters. Usually sodium is the exchangeable basic element of an active permutite. As hard water, whose hardness is usually due to soluble calcium and magnesium, passes through the softening material, the calcium and magnesium are absorbed, while sodium is set free and goes into solution, according to the following reaction:

Na_2Z	$+$	$CaSO_4$	$=$	CaZ	$+$	Na_2SO_4
Permutite, a sodium zeolite		Calcium sulphate causing hardness of water		Calcium zeolite or calcium-saturated permutite		Sodium sulphate (soluble)

Calcium is a very active displacing agent, so that in dilute solution it displaces the sodium of the permutite. Thus calcium is absorbed from the hard water and is held in the insoluble exchange-compound. At intervals, the permutite has to be regenerated, that is, it must have its absorbed calcium displaced by sodium. As sodium is not so potent a displacing agent as calcium, the displacement has to be effected by mass action—usually by a strong solution of common salt. If the softening tank is part of house equipment, a few handfuls of common salt (NaCl) are put into the tank. In regeneration, the base-exchange reaction may be expressed as follows:

CaZ	$+$	$2NaCl$	$=$	Na_2Z	$+$	$CaCl_2$
Permutite saturated with calcium		Common salt		Water-softening permutite		Calcium chloride (soluble)

Another illustration of base-exchange is illustrated when a magnesium base-exchange compound is brought in contact with a solution of potassium chloride, with the following reaction:

$$Mg\cdot(\text{alumino-silicate}) + 2KCl \rightleftarrows K_2\cdot(\text{alumino-silicate}) + MgCl_2$$

Base-exchange governed by chemical law. Gedroiz and Hissink have shown that base-exchange obeys the chemical law of mass action and equilibrium. According to Gedroiz, the law of soil base-exchange may be stated as follows: *Absorbed ions of soil compounds are displaced by other ions in equivalent ratio.*[3]

Only a limited quantity of an exchangeable basic element of a soil material can be brought into solution by the single addition of

[3] TJURIN, I. V. ACHIEVEMENTS OF RUSSIAN SCIENCE IN THE PROVINCE OF CHEMISTRY AND SOILS. Academy of Science, U.S.S.R. Russian Pedological Investigations, Vol. IV. 1927.

a displacing agent; but under leaching conditions, the displacement can finally be made complete, as Gedroiz and Hissink have shown. Moreover, base-exchange is in accord with the chemical nature of the cations concerned; for example, sodium is easily displaced by calcium, and calcium by hydrogen and ammonium (NH_4) ions. Soils vary in the total quantity of exchangeable elements they contain; hence the term "base-exchange capacity" of a soil has come into use, which means the total quantity of all exchangeable elements, including hydrogen.

When the total absorptive power of a soil is fully satisfied with metallic cations like calcium, magnesium, potassium, and sodium, that soil is said to be saturated with basic elements. When hydrogen ions (H^+) are among the cations, the condition is regarded as being unsaturated with basic elements.

It was thought that ion-exchange did not concern anions—that is, negative ions like nitric nitrogen (No_3^-), phosphorus (HPO_4^{--} or $H_2PO_4^-$), sulphur (SO_4^{--}), carbonate (CO_3^{--}), bicarbonate (HCO_3^-), chlorine (Cl^-), and hydroxyl (OH^-). Aarnio (Fin., 1927) and others have obtained results that seem to confirm the view that ion-exchange occurs among anions as well as among cations (as between OH and Cl ions), although this exchange is in a lesser degree.

Base-exchange materials, true compounds. Inorganic base-exchange materials are generally recognized as being insoluble complex compounds of alumino-silicic acids. Microscopic and X-ray examinations by Hendricks and Fry (1930) and Kelley and co-workers (1931) have shown that these compounds are ultra-microscopic, crystalline substances. They have found that these substances contain displaceable elements on the surface as well as within the crystals, the elements constituting an integral part of the crystals. Only those elements on the outside of the "crystal lattice" are exchangeable. And further, as base-exchange takes place according to the law of chemical combination, these inorganic base-exchange substances are true chemical compounds, the particles being colloidal, that is, very, very small.

Kerr (1928) and Truog and Chucka (1930), investigating the mineral composition of inorganic soil colloidal compounds, have obtained data indicating that the base-exchange component of soil colloids probably consists of a single compound the chemical composition of which seems to be $Al_2O_3 \cdot 4SiO_2 \cdot xH_2O$. Other constituents of mineral soil colloids seem to be principally free silica,

alumina, titanium oxide, iron oxide, and probably kaolinite (see Chapter 6, Specific products of rock weathering, p. 96).

Importance of base-exchange. Base-exchange is recognized as a most important basic factor in soil productivity. In it are found explanations for several important soil phenomena or conditions, including soil acidity and alkalinity, friability of some clays, fixation of potassium and ammonium (NH_4), nonfixation of nitrate nitrogen (NO_3), and "tight" or impervious clays. It is an impor-

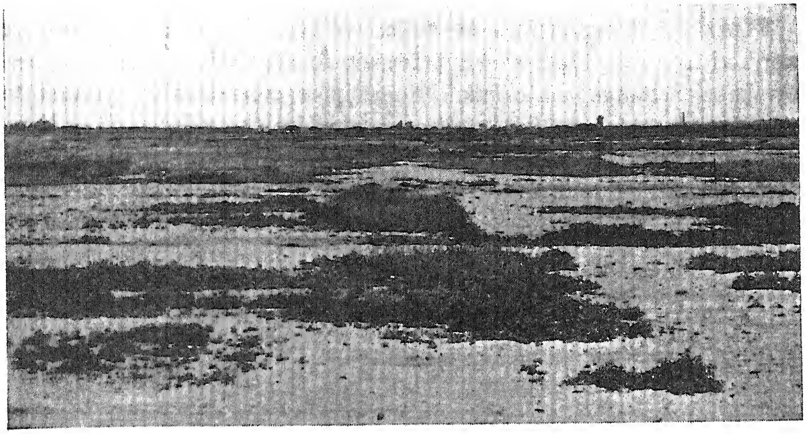

Fig. 9. An area of black-alkali soil, Fresno, Calif. In the spots where barley appears the soil was found to be almost free from injurious alkali, whereas in the barren areas the soil contained much harmful alkali. (Calif. Agr. Expt. Sta.)

tant factor in the dispersion and flocculation of clays, in the reclamation of black-alkali soils (Fig. 9), in the availability of calcium, magnesium, and potassium in soil fertility, and in connection with "buffer action" of soil materials.

Base-exchange (involving both organic and inorganic soil colloids) is only one of the fundamental factors concerned in soil fertility. One must keep in mind the many other ordinary chemical reactions that take place in soils. Not all soil constituents take part in base-exchange, although many or all of them may affect it in different ways.

Soil acidity and base-exchange. Drained upland soils in humid regions are usually more or less acid in character. This acidity is caused by the loss of basic elements, particularly calcium and magnesium, through leaching. It is generally accepted that acid base-exchange materials are the cause of this acidity. Their basic ele-

ments have been partly displaced by hydrogen. Natural clays have been found whose exchangeable hydrogen constitutes more than 60 percent of the total exchangeable elements. Such compounds may be regarded as acid clays or acid colloidal materials.

When lime carbonate is applied to an acid soil, the hydrogen of the acid-clay component is displaced by calcium, making the clay nonacid and friable. In soil fertility, calcium may be regarded as the most important exchangeable basic element. (See Chapters 16 and 17 for the subjects of soil acidity and liming.)

Fixation of potassium in soils. When a potash fertilizer is applied to a soil, the potassium is soon fixed; that is, it is absorbed by base-exchange materials. Sometimes considerable potassium may be absorbed, probably accompanied by the release of equivalent quantities of calcium and magnesium (Ch. 22). Thus potash fertilizer added to a soil may not increase the quantity of potassium in the soil solution to any appreciable degree, but instead it may increase the quantities of soluble calcium and magnesium. The fixed potassium becomes a reserve for plants, because acids or active hydrogen ions gradually set it free or make it available for plants. Evidence seems to indicate that potassium and other elements in soil base-exchange compounds can change from the insoluble to the exchangeable state, and thereby become sources of nutrients for plants.

Fixation of ammonium (NH_4). When an ammonium salt is applied to a soil, the ammonium ions (NH_4), acting as displacing agents, become temporarily fixed. Calcium or magnesium, or both, are set free and become subject to leaching. But the ammonium ions gradually pass back into solution, by the displacing action of active hydrogen ions, and are converted into nitrate nitrogen. Thus through continual use of sulphate of ammonia as a fertilizer, soils may suffer losses of basic elements, particularly calcium and magnesium; and in time the base-exchange compounds may become saturated with hydrogen, with the result that the soils become strongly acid, provided no available calcium is present and no lime is applied.

Nonfixation of nitrate nitrogen. Soils do not have the property of fixing nitrate nitrogen (NO_3) as they have for temporarily fixing ammonium nitrogen (NH_4), for two reasons: (1) ions of nitrate nitrogen are anions, and therefore do not enter into base-exchange relations; and (2) no other soil compounds are able to fix this form

of nitrogen. Nitrogen, however, is found fixed in soils in rather stable organic forms.

Fixation of phosphorus. Added anions, other than those of nitrate nitrogen, may become fixed in soils, as De Dominicis (It., 1914), Spurway (1926), and other investigators have shown. Fixation may be effected in two principal ways: (1) by ordinary chemical changes, including reactions with calcium, magnesium, hydrated ferric oxide, and aluminum; and (2) by absorption (from solutions) by colloidal materials. In soil productivity, phosphorus is by far the most important mineral element concerned among the nutrient anions. It may be readily fixed in the form of stable compounds. The soil colloidal constituents, for example, have the property of withdrawing phosphorus anions from solution.

Flocculation and dispersion of clays. When a small quantity of clay is put into distilled water, thoroughly shaken, and then allowed to stand, very fine particles will remain in suspension for a long time, especially if a little ammonia has been added. Addition of lime (particularly calcium hydroxide, $Ca(OH)_2$), to the turbid water will cause the suspended particles to collect into aggregates or floccules and to settle to the bottom. This aggregation of suspended colloidal material into floccules is known as "flocculation," and the opposite action is *dispersion,* or *deflocculation.*

Soil "humus" flocculates as well as clay, except that it requires larger quantities of a flocculating agent. Calcium salts are very effective in flocculating humus. Clay does not flocculate so readily in the presence of humus as when it is pure, owing to the protective action of the humus.

Gedroiz (1924) and Kelley and Brown (1924) have observed that the dispersability or deflocculation of soil colloids is determined largely by the kinds of exchangeable elements they contain; in other words, by the chemical nature of the colloidal materials. For example, a base-exchange compound that is saturated with sodium is much more dispersable than a similar colloid that is saturated with hydrogen.

Owing to the fact that sodium clays may become thoroughly dispersed or deflocculated, they produce physical soil conditions that are unfavorable for plant growth. In contrast, calcium or lime clays are granulated and porous. Baver (1929) has found that the size of calcium-clay particles is about eight times as large

as those of sodium clay, and that calcium clay is much more permeable.

Alkali soils and base-exchange. Kelley, Thomas, and Brown (1928-1934) have found that base-exchange is an important factor in the reclamation of unproductive "black-alkali" soils. In addition to having an excess of soluble salts, which may be readily leached out by flooding and drainage, these soils may have an excess of sodium in their base-exchange materials. Inasmuch as these

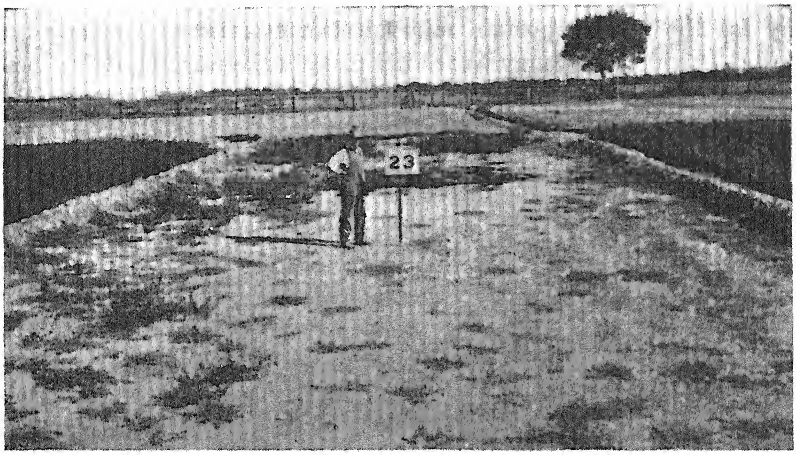

Fig. 10. Leaching of black-alkali soil is not quickly effective when unaccompanied by other treatment. Plots to left and right were treated with sulphur (Fresno, Calif.). (See Fig. 11.)

sodium complexes are insoluble, and hence cannot be leached out (Fig. 10), it is important that they be converted into calcium compounds in order to render them noninjurious to plant growth. In bringing about this change, calcium has been found to be the most effective agent.

Restoration of calcium in the base-exchange compounds of alkali soils that contain both sodium and calcium may be gradually effected through leaching out the soluble salts by frequently flooding the land, provided the land is properly drained. Removing the soluble alkalies from the soil mass allows calcium to displace the sodium, according to the chemical law of mass action and equilibrium. The displaced sodium is removed by subsequent leaching. With soils whose base-exchange materials contain much sodium, it may be advisable to supplement the leaching water with gypsum

($CaSO_4$) or elemental sulphur (S). Calcium salts dissolved in irrigation water aid materially in the reclamation of alkali soils. If much calcium is present, good results may be obtained without the use of gypsum or sulphur.

Calcium may be quickly restored in the base-exchange compounds of sodium alkali soils, according to Kelley and Thomas, by applying elemental sulphur, iron sulphate, or alum (potassium-aluminum sulphate) to these soils. This will bring calcium (already present

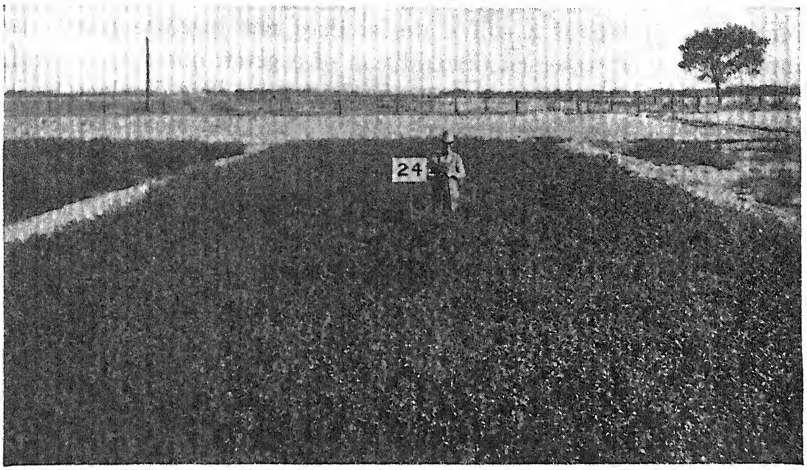

Fig. 11. This black-alkali soil quickly responded to sulphur which was inoculated with sulphur-oxidizing bacteria. The sulphur (activated) liberated soil calcium which, in turn, displaced the sodium in the base-exchange compounds, thereby making possible the growth of alfalfa.

in the soils) into solution, following neutralization of practically all the soluble carbon dioxide. Farm manures may also be used for this purpose. Carbon dioxide formed by plant roots and in decomposition of organic matter will cause displacement of sodium. Sulphur has proved to be an effective and economical material to use in the reclamation of alkali soils that contain much calcium carbonate (Figs. 10 and 11).

Soil injury from sodium. Closely related to the alkali-soil problem is the development of "tight" or sodium clays by the action of sodium that may accumulate in certain soils through the sole and continual use of nitrate of soda as fertilizer. This occurs in the absence of calcium or magnesium, or both. Ordinarily, up to a certain point, when calcium is present or is added as carbonate or

as gypsum (as in superphosphate), the formation of easily dispersible sodium clays is unlikely, owing to the fact that calcium ions are much more effective than those of sodium in competing for base-exchange materials. In calcareous soils, in which OH ions are responsible for dispersion of colloids, calcium carbonate does not help.

Buffer action and base-exchange. By "buffer" action is meant the resistance of a soil material to the action of acids and bases in effecting a change in its reaction. For example, the hydrogen-ion concentration of a soil material does not increase nearly so much as that of water on the addition of a given quantity of acid. The reason for this is that the active hydrogen ions displace basic elements of the soil base-exchange materials. The more exchangeable basic elements a soil material contains and the greater its colloidal content, the greater is its resistance to change in reaction. Accordingly, fine-textured soils are sometimes described as being well-buffered or as having high resistance to change in reaction.

Buffer action concerns base-exchange, and it reflects the comparative stability of base-exchange compounds. Acid base-exchange compounds are more stable than the acids and salts of soil solutions. This explains the importance of buffer action in soil fertility, in regulating the reaction of soil solutions. Buffer action principally concerns the displacement of basic elements by hydrogen.

Electrochemical nature of soil colloids. Aqueous colloidal suspensions are commonly called "sols," and their particles bear electric charges. Evidence indicates that a sol particle consists of an insoluble particle, either positively or negatively charged, plus certain stabilizing ions. Hence the term "colloidal system." The positive particles of the ferric or aluminum hydroxide sol, for example, have Cl^-, SO_4^{--}, or other stabilizing charges. The condition within a colloidal system of soil sols is negative. The electric charges of sol particles, which determine the stability of the sol, may be greatly affected by the presence of an electrolyte (salt, acid, or base) [4] in the liquid in which a colloid is dispersed or suspended.

Electrolytes have the power to coagulate sols by neutralizing the charges that stabilize them, thus causing flocculation or precipita-

[4] An electrolyte is so called because it can conduct an electric current when dissolved in water. When a current is passed through a soil solution, for example, the electrolytes present suffer decomposition (electrolysis). Ions that give rise to products evolved at the negative electrode (cathode) are called "cations," like Ca^{++}, Mg^{++}, K^+, and H^+; and ions that may be set free at the positive pole (anode) are called "anions," like SO_4^{--}, NO_3^-, and OH^-.

tion. The precipitates are called "gels." In soils, colloidal precipitates may be finely divided materials like clays or indurated masses like certain forms of iron hydrate.

The opposite of coagulation, or gelation, is called "peptization" which means the stabilization of sols. Dilute hydrochloric acid, for example, tends to increase the stability of positive ferric and aluminum hydroxide sols; whereas small quantities of sodium, potassium, and ammonium hydroxides tend to peptize negative sols, like those of soils, owing to the action of the hydroxyl ions (OH^-). According to Anderson and Mattson (1926), soil alumina-silica sols take on hydroxyl ions readily (hydrolysis), which increases the dispersion of the colloidal material and hence the stability of the sols. Such a reaction results when a dilute solution of an alkali hydroxide is used to deflocculate a clay.

Organic soil colloids, which are intimately associated with mineral colloids, have electrochemical properties similar to those of the inorganic colloids. Electrochemical properties of soil colloids are greatly affected by their exchangeable elements or ions.

ORGANIC MATTER

Organic matter constitutes the principal carbonaceous and nitrogenous constituents of soils. It is also an important source of mineral nutrients which become available to plants on decomposition, and it serves as sources of carbon for soil micro-organisms. Some of the soil phosphorus occurs in soluble organic forms.

The quantity of organic matter in soils varies widely, from a comparatively small percentage in poor sands to more than 70 percent in peat soils. The rate of natural accumulation of organic matter is determined largely by the nature of the vegetable growth, temperature, precipitation, and drainage.

It is a common fact that accumulation of soil organic matter is greater under grass than under forest cover. This is definitely shown when one compares, for example, the dark-brown soils of tall-grass prairies with grayish-brown forest soils.

No universal relation exists between annual precipitation and soil organic matter, although in certain regions there is a very definite relationship, as may be seen in the decreasing quantities in the soils between central Iowa (U. S.) and central part of Wyoming (Fig. 21). Marsh-border, muck, and peat soils are also

good examples to show the effects of poor drainage on the accumulation of organic matter.

The relation of soil organic matter and nitrogen to the average annual temperature of a region can best be expressed in terms of the ratio between carbon and nitrogen contents, regardless of the quantity of organic matter present.

Carbon-nitrogen ratio in soils. Sievers and Holtz (1923), Jenny (1929), and Dean (T. H., 1930) have shown that the carbon-nitrogen ratio decreases, or narrows, with increasing average annual temperature. Ordinarily, in original vegetable residues the proportion of carbon to nitrogen varies from about 20 to 1, as in grass, to about 40 to 1, as in straw. In some residues the ratio is as high as 80 to 1. In wood fiber it may be as high as 430 to 1. In tissues of leguminous plants, the ratio may be as low as 15 or 25 to 1. In soils, however, the general ratio is much narrower, commonly about 10 or 12 to 1, being widest or highest in surface layers, and decreasing with depth. Lunt (1932) has reported C-N ratios as wide as 24 to 1 in forest soils of the New England States.

C-N ratio under like temperatures. Jenny (1930) has established some very interesting facts regarding the C-N ratios in well-drained upland loams and silt loams from the western part of Colorado to the eastern shore of New Jersey along the isotherm that includes average annual temperatures that range from 51° to 53° F. Along this isotherm he found fairly constant C-N ratios, averaging 11.6 to 1 for grassland soils and 10.9 to 1 for forest soils.

Relation of C-N ratio to productivity. In their investigation of 63 soils of 12 States, Leighty and Shorey (1930) have found that the C-N ratios in topsoils to depths of 5 and 12 inches ranged from 7.1 to 1 in a fine sandy loam of the coastal plain of Virginia to as high as 26.5 to 1 in a coarse sandy loam of South Carolina. In his study of 50 British and some foreign soils, McLean (Eng., 1930) has found a range in C-N ratios of from 6.5 to 1 to 13.4 to 1, and from 2 to 1 to 23 to 1 in the foreign soils. These investigators have failed to find any correlation between C-N ratio and soil productivity.

Chemical nature of organic matter. Space will not allow a detailed discussion of the chemical composition of the organic substances in soils. However, a few general statements may be made.

A very large number of organic substances occur in soils, representing not only all stages of decomposition from original plant and

animal residues to practically nondecomposable waxy substances resulting from decay, but also including a great number of organic salts and other compounds which originate as by-products in decomposition. Inasmuch as plants manufacture a large number of organic substances through progressive stages of synthesis—from comparatively simple sugars and simple amino-acid compounds to extremely complex nucleoproteins—it follows that the decomposition of these plant substances in soils gives rise to a large number of organic compounds which correspond to the stages in the original synthetic process. Some of these substances contain only carbon and hydrogen, as hydrocarbons; some contain carbon, hydrogen, and oxygen, like carbohydrates; others consist of carbon, hydrogen, oxygen, and nitrogen; while many others contain carbon, hydrogen, oxygen, nitrogen, and mineral and other elements.

Carbon an index of organic matter. The nitrogen content of soils indicates roughly the comparative quantities of the organic matter that they contain. To illustrate: An average nitrogen content of 0.037 percent for jack-pine sands indicates a very low content of organic matter; 0.06 percent of nitrogen for brown silt loams (forest soils) shows a medium content of organic matter; an average of 0.32 percent of nitrogen for prairie silt loams means a high content of organic matter; and 3.5 percent of nitrogen for a peat soil indicates the presence of a very high quantity of organic matter.

Because of the important role that organic matter plays in soil productivity, the quantity a soil contains has considerable significance. The quantity of organic matter in a mineral soil may be approximated by first obtaining the total carbon either by wet or dry combustion, then multiplying the percent of total carbon thus obtained by Van Bemmelen organic-matter factor 1.724, which factor is based on the average content of 58 percent of organic carbon in soil organic matter. In peat and low moor soils, according to Waksman and Hutchings, the factor recommended is 1.862.

Chemical nature of humus. Of the different kinds of soil organic matter, "humus" is most interesting, particularly from the chemical point of view. Humus attracted the attention of investigators as early as 1786 and 1797; and it has received much attention in modern soil research. Although considerable study has been given soil organic matter since systematic inquiry into this problem was initiated by Hoppe-Seyler (Ger.) in 1899, a clearer understanding

of the origin and chemical nature of humus compounds was not gained until the part played by soil micro-organisms was taken into account. Physicochemical processes are also involved in humus formation.

Humus compounds are dark-colored, and they originate principally from the action of soil micro-organisms on residues of higher plants and animals. They are chemical complexes, and they differ

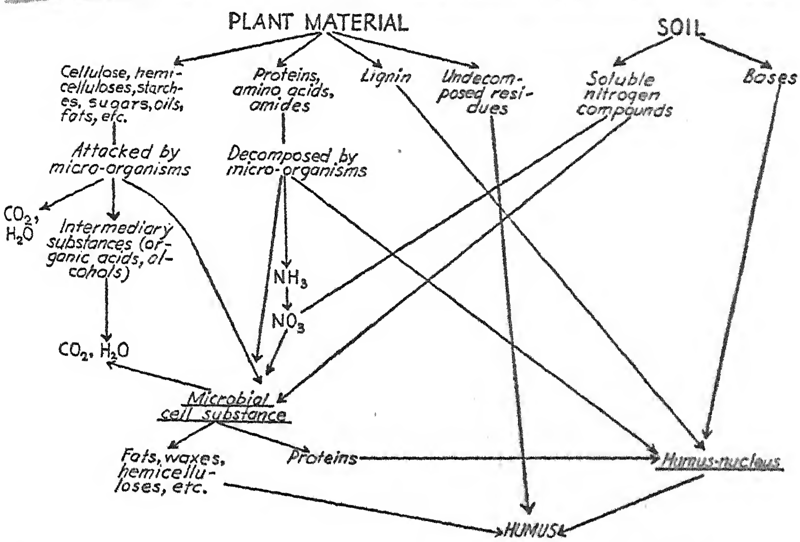

Fig. 12. The mechanics of humus formation, in decomposition of plant residues in soils. "Humus-nucleus" constitute the principal fraction of humus, peat soils, and composts.

according to kind of plant or animal residue, micro-organisms, moisture, temperature, aëration, and conditions, as regards chemical reaction, under which they form. According to Page (Eng., 1927), soil humus is a lignin-protein substance which makes nitrogenous materials resistant to decomposition.

Waksman (1929) has summarized the origin and chemical nature of humus substances as follows: In the process of decomposition of plant residues in a soil, the water-soluble substances are acted upon first; these are followed by the celluloses, certain hemicelluloses, proteins, and then lignins. The lignins are most resistant to decomposition in aërated soils, and they are practically undecomposed in water-logged soils. In decomposition of carbohydrates and proteins, micro-organisms synthesize considerable quantities of cell

substances, in which process nitrogen and some phosphorus are built into their cell complexes. These cell complexes, in turn, undergo decomposition, and the by-products that result therefrom are rich in nitrogenous materials, gums, and fatty and waxy substances. Resistant plant materials like lignins and resistant synthesized cell substances of micro-organisms, which go to make up humus, constitute a large part of soil organic matter.

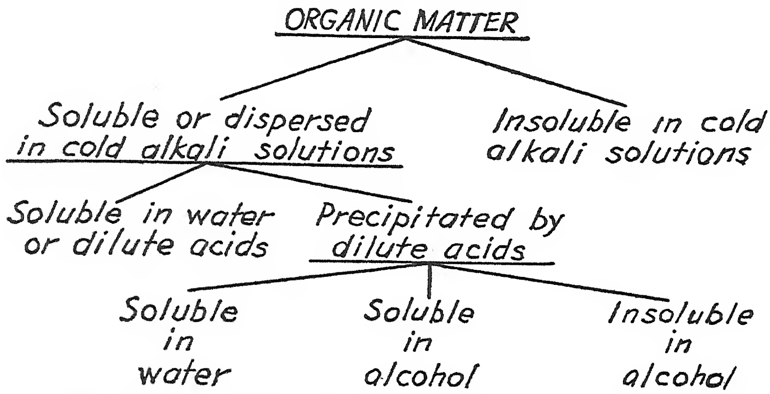

Fig. 13. Chemical nature of humus, based on solubility.

The mechanism of humus formation is shown schematically in Figure 12, after Waksman and Iyer (1932). The chemical nature of humus substances is suggested in Figure 13.

Chemical absorption by humus. It has already been pointed out that soil organic colloidal materials have the property of chemical absorption as do the inorganic colloidal compounds. They are particularly potent in withdrawing ions like Ca^{++}, Mg^{++}, NH_4^+, K^+, $H_2PO_4^-$, and HPO_4^{--} from soil solutions. McGeorge (1930) has shown that aluminum ions of sulphate and chloride cannot enter the organic base-exchange complexes and displace divalent and monovalent ions. According to their chemical nature as regards content of exchangeable elements, humus materials may be either highly acid or distinctly alkaline.

That humus may play a greater role in soil base-exchange than mineral colloidal matter was suggested by Hissink (Holl., 1928) and Gedroiz (Russ., 1929). Smolek (Czech., 1931) has reported much greater absorption of calcium, magnesium, sodium, potassium, and hydrogen by organic than by mineral soils. In his study

of base-exchange property of soil organic matter, Mitchell (1932) found that organic matter of mineral soils contributed to their base-exchange properties in degrees ranging from 41 to 65 percent.

Humus as a buffer material. Humus is a most important buffer material that enables soils to resist the action of acids. Baver (1931) has found that in a brown silt loam (forest soil) buffer action of organic colloids sets in only under slightly acid, neutral, and alkaline conditions. He inferred from this that organic colloids are responsible for buffer action in neutral and nonacid soils. The work of Hissink, Gedroiz, Smolek, and Mitchell on organic matter (referred to above) suggests high "buffer capacity" of this class of soil constituents.

SOIL SOLUTIONS

The water that a moist soil holds against gravity is in closest contact with its physical constituents and with plant roots and micro-organisms. Certain substances are dissolved in this water, forming a very dilute solution, called *soil solution,* which Cameron (1910) regarded as the natural culture solution for crop plants. The soil solution covers the soil particles in the form of thin films, and *growing land plants deal more with this solution than with soil particles or with organic matter.* Knowledge of soil solutions is rather meager, owing to the difficulty of getting them away from the soil particles without changing their nature. A very satisfactory method has been devised by Ischerekov (Russ., 1907), which consists in displacing and driving out the solution of a soil through the use of ethyl alcohol.[5]

In ordinary cultivated soils, the concentration of the solutions or the percentage of dissolved substances in them varies from about 0.05 to 0.2 percent. The solutes, or dissolved substances, are derived from slowly dissolving mineral particles, decomposing organic matter, base-exchange compounds, organisms, added fertilizers and other substances, and from plant roots.

Chemical constituents of soil solution. The chemical constituents of soil solutions in normal cultivated soils may be stated as follows: They contain all the nitrates available to plants, oxygen, carbon dioxide, and bicarbonates, with some organic substances (including soluble but unavailable organic phosphorus), sodium,

[5] PARKER, F. W. METHODS OF STUDYING THE CONCENTRATION AND COMPOSITION OF THE SOIL SOLUTION. *Soil Science,* Vol. 12, No. 3. 1921.

magnesium, silicon, chlorine, sulphur, much of the available potassium, only a fraction of the available phosphorus, and a trace of ammonia.

Soil solution and plant nutrition. Results of leaching experiments obtained by investigators seem to indicate that it is impossible to bring to an end the solubility of certain soil constituents by successive leachings with water. This significant fact has a vital bearing on plant nutrition, because continued solubility is usually necessary throughout the growing period of plants.

There is no scientific support to certain claims that have been made that the concentration of soil solutions is adequate for plant growth. To illustrate: In their inquiry into this problem, Parker and Pierre (1928) found that some soil solutions contained phosphorus in concentrations insufficient to support plant growth, yet the soils considered were able to produce good yields (Indian corn), thus indicating the necessity of close root-soil contact (Ch. 9).

Dynamical nature of soil solutions. Whitney and Cameron (1903-1904) contended that the composition of soil solutions was practically the same in all soils. On the contrary, several investigators have obtained different results, establishing the facts that both the composition and concentration vary according to kind of soil, natural productivity, crop growth, season of year, soil treatment, and water content of soils. Furthermore, Hoagland and Sharp (1918) have shown that soil solutions are not saturated solutions.

As soil solutions are affected directly and indirectly by such factors as precipitation and irrigation, temperature, micro-organisms, fertilizers, and plant roots, they undergo constant changes both in composition and concentration. Nitrates, bicarbonates, chlorides, and sulphates are easily lost from soil solutions through soil leaching, particularly the nitrates if they are not utilized by plants. Nitrates are perhaps the most variable constituents. The fact has been established that soil solutions in poor soils do not contain adequate quantities of nutrients, whereas solutions in fertile soils are rich in dissolved nutrient substances.

Soil solution and base-exchange. Base-exchange compounds in a soil bear a very important relation to the soil solution; they act especially as regulators of its reaction. If the acids which result in a soil from decomposition, chemical changes, and biological activities were allowed to accumulate, the soil solution would also

become excessively acid. But as these acids react readily with displaceable basic elements, the acidity of the soil solution is controlled. In a soil on which a crop is growing, the soil solution probably acts as a most important medium between the base-exchange compounds and the plant—that is, in conveying nutrient elements and in controlling the acidity of the soil zones immediately around the plant roots.

SOIL AIR

The nitrogen content of air in arable soils is practically the same as that of ordinary air, except in paddy-rice soils, for example, where a large part of the nitrogen may be derived from organic matter. The carbon dioxide and oxygen of the air in upland soils changes continuously, owing to biological activities and chemical reactions.

Leather (India, 1915) has found that in the surface 6-inch layer of soils, diffusion of carbon dioxide into the atmosphere and of oxygen into soils takes place very rapidly. His data in the accompanying table are full of interest:

AVERAGE PERCENTAGES OF CARBON DIOXIDE AND OXYGEN IN SURFACE 6-INCH LAYER OF SOILS [6]

Gas	Fallowed Land		Green-manured Land	Swamp Rice Land	Gases Near Roots of Corn
	Before Rain	After Rain			
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Nitrogen	78.05	78.83	79.18	85.59	80.15
Oxygen	20.40	19.26	7.71	0.54	9.00
Carbon dioxide	0.58	0.95	12.03	4.42	9.11

During dry seasons, soil air is rich in oxygen and poor in carbon dioxide. Soon after heavy rains, however, the oxygen content rapidly diminishes and the carbon dioxide content increases. The importance of oxygen and carbon dioxide in cultivated soils is discussed in Chapter 9.

SOIL ACIDITY AND ALKALINITY

The reaction of soil materials, whether acid, neutral, or alkaline, is determined by lack or prevalence of basic elements, particularly calcium, magnesium, and (in alkali soils) sodium. Lack of these

[6] LEATHER, J. W. SOIL GASES. Mem. Dept. Agr. India, Chem. Ser. 4, pp. 85-134. 1915.

elements, or soil acidity, results from leaching. Inasmuch as percolating rain water is the principal leaching agent, development of acidity in mineral soils starts at the surface. Thus in some soils the reaction at different depths from the surface down to the substratum below the subsoil may vary from strongly acid to distinctly alkaline. The reaction of soil material at different depths in a soil, from surface downward, may be called *"solum reaction."* Different types of solum reaction, acidity, and alkalinity may develop, as based on degree of reaction. (Soil v. solum, Ch. 6.)

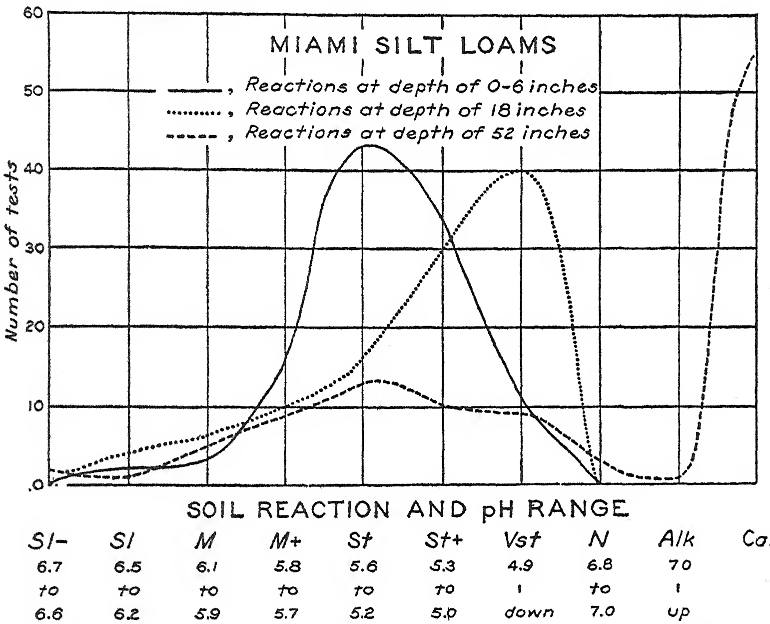

Fig. 14. Statistical mode applied to solum acidity of 103 brown forest soils, showing "greatest frequency" of reactions at three depths. Reactions range from slightly acid (Sl) to calcareous (Cal). M, Medium acidity. St and Vst, Strong and very strong acidity. N, Neutral reaction. Alk, Alkaline reaction. (See Fig. 15.)

Types of solum acidity. The author (1925)[7] has investigated the solum acidity of 381 soils in Indiana, representing 5 different groups of similar soils, as follows: (1) 103 brown forest upland silt loams (*Miami silt loam*), locally called "maple-walnut land"; (2) 60 gray, naturally poorly drained forest silt loams (*Crosby silt loam*), locally called "white-oak soil" and "jack-oak land"; (3)

[7] Unpublished data.

69 dark-brown prairie upland silt loams (*Carrington silt loam*), commonly called "bluestem land"; (4) 85 brownish-black silt loams (*Brookston silt loam*), locally called "medium soils," because under natural conditions they occurred in alternately wet-and-dry areas between either the brown forest soils or the prairie soils and water-logged depressions; and (5) 64 black silt loams

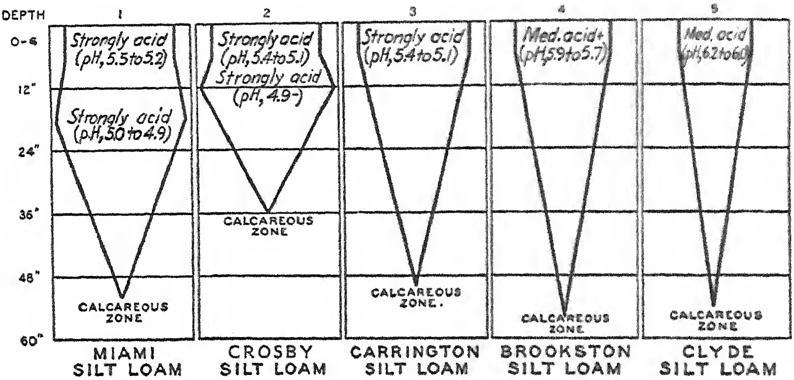

Fig. 15. Types of solum acidity.

(*Clyde silt loam*), which have developed in depressed, water-logged areas and which were locally named "black gumbo land." [8]

All reaction determinations in the above cases were made in the field, including acidity, neutral point, and alkalinity at varying depths. Bromthymolblue was used in testing for acidity and alkalinity, and dilute hydrochloric acid, for lime carbonate. Usually at a given depth in the soils of the different groups the degree of acidity varied rather widely. The type of solum acidity for each group was determined not according to averages, but according to the most common reaction at any given depth, particularly in those soils regarded as typical for each group. The concept of "greatest frequency," which is designated in statistics as "mode," has to do with actual facts (Fig. 14). Averages are abstract concepts, and have no reality in nature. The results of this study are shown diagrammatically in Figure 15. The 6-inch surface layers of practically all soils examined had been thoroughly mixed as the result of cultivation.

In a study of soils of eight Illinois experimental fields, Lunt (1929) found that acidity decreased with depth. Norton and Bray

[8] Journal of the American Society of Agronomy, Vol. 18, No. 12. Dec., 1926.

(1929) have reported types of solum acidity somewhat similar to the first two types shown in Figure 15. Soil acidity and alkalinity are more fully discussed in Chapter 16.

AVAILABILITY OF NUTRIENT ELEMENTS

The chemical nature of soils may indicate potential productivity, because there may be a close relation between the total quantity of nutrient elements in soils and their ability to grow crops. However, the most important factor in crop production, so far as the chemical composition of soils is concerned, is availability of the nutrient elements. This may mean not only solubility, but also the presence of nutrient elements in such forms or conditions that plants can obtain them during growth, when their roots establish the closest contact with the complex materials that compose soils. This subject is fully discussed in Chapters 20, 21, 22, and 23.

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REVIEW QUESTIONS

1. Explain the chemical composition that soils have.
2. Discuss the relationship between texture and chemical composition of soils.
3. What is the difference between chemical absorption of soil materials and base-exchange? Illustrate.
4. What is the relationship between soil acidity and base-exchange?
5. Compare the fixation of potassium and phosphorus in soils.
6. Explain the behavior of ammonium and nitrate ions toward soil base-exchange compounds. What is the significance of this behavior?

7. Explain the difference between flocculation and dispersion of clays. Illustrate the importance of these actions in relation to soils.
8. Explain why an excess of sodium may prove to be injurious to soils. What is the remedy?
9. What is the difference between base-exchange property and electrochemical nature of soil colloids?
10. Distinguish between soil organic matter and humus.
11. With what do growing plants deal primarily in soils? Discuss this relationship.
12. Compare the chemical composition of soil air and the atmosphere.
13. Explain the types of solum acidity illustrated in Figure 14.

CHAPTER 5

MICROBIAL POPULATION OF SOILS

The importance of the comparatively recent discovery of micro-organisms in soils is not even yet fully appreciated, but it is no exaggeration to say that if it were not for these micro-organisms, which have undoubtedly been a part of the soils of the world for millions of years, it would be absolutely impossible for human life to continue in existence.

Soils have remained sufficiently constant in composition and condition long enough to allow these micro-organisms to adapt themselves to them and to make them their habitats. These organisms live mostly on the surface of colloidal particles and partly in the soil solutions. They consist of an uneven proportion of minute plants and animals—those which belong to the plant kingdom far outnumber those of the animal kingdom. Thus a soil has a special microflora and microfauna which constitute an invisible and a most complex population. Moreover, Conn (1927) has found practically the same flora in a large number of different kinds of soils.

Classification of soil organisms. According to Waksman, soil organisms may be classified as shown in the table at the top of page 82.

Besides those classified, there are other bacteria which are so small that the highest magnification known is insufficient to reveal them to the eye. They are known only by the effects that they produce, and they are called "ultra-microscopic organisms" and "filter-passers."

So far as is known, bacteria predominate both in number and activities over all other groups of soil organisms. They are classed as *heterotrophic* (saprophytic) and *autotrophic*—that is, bacteria which consume substances that are built up by other organisms, and bacteria that thrive on inorganic substances.

Density of soil population. An idea of the density of soil population may be gained from the number of bacteria. Investigators

- Soil Organisms
  - Flora (plants)
    - Bacteria
      - Heterotrophic
        1. Nitrogen-fixing
           a. Symbiotic
           b. Nonsymbiotic
        2. Bacteria that require combined nitrogen.
      - Autotrophic
        - Bacteria that oxidize nitrogen, sulphur, iron, hydrogen, and carbon compounds, and sulphur and hydrogen.
    - Fungi
      - Yeasts
      - Molds
      - Actinomycetes [1]
    - Algæ
      - Blue-green
      - Diatoms
      - Grass-green
  - Fauna (animals)
    - Protozoans
    - Nematodes
    - Rotifers
    - Worms
    - Insects, etc.

have found from 320,000 to 500,000 bacteria in a gram of sandy soil material, and from 360,000 to 600,000 in loamy material. In soils that are well supplied with organic matter, as many as from 2,000,000 to 200,000,000 bacteria per gram of material have been found, depending on such factors as kind of soil, soil reaction, soil treatment, season, and water content of soils. Poor sandy soils, on the other hand, may contain as few as 25,000 or 100,000 per gram of material, and in some very acid peat and forest soils, very few have been found.

In humid regions, soil population is most dense in the surface layers to a depth varying from 1 to 3 inches. Deeper down, the number of micro-organisms decreases, practically disappearing at a depth of about 3 or 3½ feet. Bacteria have been found to go deeper in cultivated than in noncultivated soils. In soils of arid regions, micro-organisms penetrate deeper; in places, to a depth of 6 feet. C. B. Lipman (1912) has found that in these arid soils the number of bacteria may be greater at a depth of 24 inches than at a depth of 6 inches.

Waksman (1916) observed that in soils under shade, such as

[1] *Actinomyces* (genus) is commonly defined as a group of filamentous bacteria.

under orchard and forest trees and grasses, bacteria were concentrated at a depth of 1 inch; while in similar soils exposed to the sun, they were most numerous at a depth of 4 inches.

Cutler and co-workers (Eng., 1920) have shown that in fertile soils hourly, daily, and seasonal oscillations, or large fluctuations, occur in the size of the micro-organism population.

Importance of soil micro-organisms. The effects wrought by soil bacteria, fungi, actinomycetes, algæ, and protozoans are manifold. Some bacteria, both free-living and those associated with leguminous plants, are able to fix inert and useless nitrogen from the atmosphere, and supply it to plants in the form of nitrogenous nutrients. Bacteria and fungi break down dead plant and animal substances, thereby causing the "dust" from which they came to return to the earth to become sources of available nutrient elements for plants. Were it not for these micro-organisms, the earth's surface would soon be cumbered with dead plants and animals in which the material basis of all life—carbon, nitrogen, phosphorus, and other elements—would be locked up beyond recovery. Even the tiny algæ absorb carbon dioxide from the air and fix the carbon in their bodies; and ultimately, after death, they supply organic substances to soil bacteria for the enrichment of soils. Furthermore, the fertilizing value of manures, green manures, composts, and many commercial fertilizers, in rendering available the nutrient elements contained in them, depends on the action of soil micro-organisms. Because of the fact that the greater part of plants is cellulose, cellulose-decomposing organisms are very important.

Needs of soil organisms. All micro-organisms require favorable temperature and adequate moisture for optimum growth, and they need materials to supply energy. They also must have nitrogen, carbon, phosphorus, and other elements in building their protoplasm or cell substances. Energy is derived principally from organic materials (including carbohydrates and nitrogenous matter) and through oxidation of inorganic substances. Nitrogen is obtained from various sources, including ammonia or ammonium compounds, nitrates, nitrites, and nitrogenous organic compounds. Carbon may be derived from carbon dioxide of the air, soil solutions, and from organic compounds.

Carbon-nitrogen relations. There are certain relations between carbon and nitrogen contents of soils and micro-organisms which

have important economic significance. One of these relations concerns the equilibrium between soil organic carbon and nitrogen, or the C-N ratio (Ch. 6). Ordinarily when plant residues undergo decomposition, considerable quantities of carbon dioxide are given off, while comparatively limited quantities of ammonia or nitrates are formed. This process continues until a more or less constant C-N ratio results, averaging about 10 or 12 to 1. Further decomposition of humus substances results in a more or less parallel liberation of carbon and nitrogen as carbon dioxide and ammonia, the latter being converted into nitrates.

The greater the quantity of carbon assimilated by soil organisms, the greater is the quantity of nitrogen utilized in building up protoplasm. Hence, the greater the quantity of readily available carbohydrates present, the more available soil nitrogen will the micro-organisms consume, even to the extent of depriving crop plants of it.

Decomposition is complex. Decomposition of plant and animal residues in soils is a most complex process. This process becomes all the more complex when we consider the fact of the interaction of the different groups of organisms. Autotrophic bacteria, for example, utilize by-products formed by heterotrophic bacteria, including various minerals, nitrogen compounds, ammonia, and hydrogen sulphide. Heterotrophic bacteria, on the other hand, utilize products formed by autotrophic bacteria, including organic acids and other complex compounds. Thus in a complex physical and chemical soil medium, micro-organisms carry on their activities not as individual groups, but together as a soil population. Moreover, a soil does not represent a homogeneous biological entity, but rather a whole series of complex biological activities that may be in progress at the same time.

Organic matter, roots, micro-organisms. According to Thom and Smith (1933), organic matter on the surface of the ground is broken down by enormous numbers of bacteria, fungi, and other organisms without producing any change in the soil micro-population beneath. Green manures incorporated into soils of good tilth are decomposed mainly by bacteria. These investigators also found that, owing to acid excreted by plant roots, the biological conditions within a very narrow contact zone around a growing root are determined by root acidity rather than by soil reaction (see Index).

Origin of soil microbiology. Primitive people concluded very early that, although plants originated in the ground, after death they decayed and returned to the earth from whence they came. They thought of themselves in a similar manner, according to the Biblical record which states that a man is dust and that unto dust he shall return (Gen. 3:19).

For many centuries these things were accepted as a matter of fact; nobody seemed to have thought that there was any explanation for decay. If anybody did, he had neither knowledge nor means for making any exploration into this field of inquiry. The day of discovery came when Van Leeuwenhoek (1683), a Dutch naturalist, with simple magnifying lenses, demonstrated the existence of bacteria in water, saliva, and dental tartar. Scientific inquiry into soil life did not begin until nearly 200 years later. During these two centuries, however, the science of bacteriology and bacteriological technique developed, and also the biological causes of fermentation and putrefaction were established.

Applying the discovery that Schloesing and Müntz (Fr.) had made in 1877, which was that nitrification in sewage was caused by living agents, Warington (Eng., 1878) found that the formation of nitrates in soils (the source of nitrogen for plants) was the result of two separate processes, and that it involved two different micro-organisms.

Warington worked for 12 years with a view to determining what these organisms were, but without success. In 1890 they were isolated by Winogradsky, a Russian scientist working in Paris. His success came only after he had changed the accepted method of inquiry by using ammonium sulphate instead of nitrogenous organic matter in his nutrient mediums.

Since 1878, soil biological research has progressed rapidly; but although considerable progress has been made, comparatively little is known of the nature and activities of many of the organisms that make up the complex population of soils. However, we shall consider these organisms briefly, particularly their activities, with a view to gaining a general knowledge of this microbial population.

ORGANISMS THAT DECOMPOSE ORGANIC MATTER

Micro-organisms that break down complex plant and animal residues are of fundamental importance. In decay (aërobic de-

composition)[2] they produce nitrates as end-products, and render available other elements which are essential in plant nutrition. A general knowledge of the importance and activities of these organisms may be gained through a study of their actions on two principal groups of organic matter that constitute plant and animal residues—non-nitrogenous and nitrogenous substances.

Decomposition of carbohydrates. Carbohydrates comprise most of the non-nitrogenous compounds, including the simpler sugars

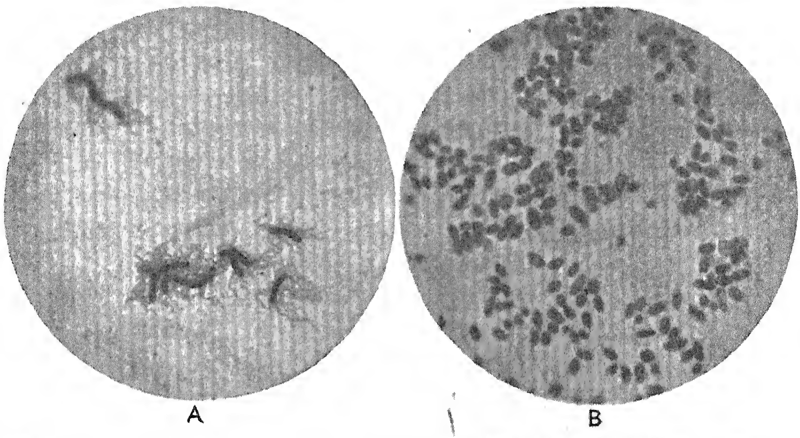


Fig. 16. Soil bacteria, heavily stained, as they appear under a microscope. A, Cellulose-decomposing bacteria (*B. cytasens*). B, Free-living nitrogen-fixing bacteria (*Azotobacter*).

and starches, pentosans, celluloses, ligno-celluloses, and lignins, named in about the order in which they are broken down. The last three materials constitute the bulk of plant residues and the sources of much of the humus in soils.

Carbohydrates are the sources of energy for a great variety of soil organisms (Fig. 16). The principal products resulting from their decomposition are carbon dioxide, water, lime carbonate, methane (particularly in marsh and swamp soils), and humus.

The effect of cellulose-decomposing organisms on crop production may be illustrated as follows: When considerable straw or coarse litter is added to a soil, it causes a rapid development of microorganisms, owing to the addition of a large quantity of readily decomposable energy-producing substances. Inasmuch as nitrogen is required in the building of their protoplasm, these organisms,

2 Decomposition in the absence of oxygen is *fermentation*.

including fungi, actinomycetes, and bacteria, may actually rob the crop of nitrates which are very important in plant growth.

Another illustration may be given: When a low-lying field on which maize or small grain is growing becomes flooded and the water remains for a considerable length of time, formation of soil nitrates will not only cease, but also denitrifying bacteria, which obtain energy from cellulose under such conditions, will reduce any nitrates present in order to obtain their supply of oxygen. This results in a disappearance of soil nitrates and loss of nitrogen, as is indicated by the yellowing of the leaves.

Decomposition of nitrogen compounds. Among the organic nitrogen-containing compounds that are left in or are added to soils are plant proteins, nitrogenous substances that are formed within the cells of millions of micro-organisms, animal manures, green manures, and organic fertilizer materials. Decomposition of these materials results from the activity of a large number of different kinds of bacteria and fungi. Here the principal by-products are ammonia, nitrates, carbonate of lime, carbon dioxide, and compounds or salts which contain essential mineral plant nutrients.

Ordinarily, the nitrogen is released as ammonia, and the organisms that bring this about derive their energy in decomposing these organic compounds. These organisms would use more easily available energy if it were offered them, such as straw and other substances that are comparatively rich in carbohydrates. These carbohydrates stimulate their activity and increase their demand for nitrogen. Soil nitrates are thus attacked. Accordingly, large additions of carbohydrates, such as sugar-containing material, to a soil may cause depression of nitrates.

The formation of ammonia as a by-product in decomposition of nitrogenous compounds is called "ammonification" which is caused by a large number of micro-organisms, including bacteria, fungi, and actinomycetes.

NITRIFICATION, NITRATE REDUCTION, DENITRIFICATION

Certain soil micro-organisms are concerned with the formation of nitrates, the most important sources of nitrogen for plants; whereas other organisms, under certain conditions, may destroy nitrates. The processes involved in these activities are *nitrification, nitrate reduction,* and *denitrification.*

Nitrification. Nitrification is the formation of nitrates from ammonia by two groups of bacteria. One group first converts ammonia into nitrites, and the other immediately changes the nitrites into nitrates. The number of nitrifying bacteria in soils has been found to vary from a few to 10,000 per gram of soil material.

Nitrate reduction. A large number of organisms—including bacteria, fungi, and actinomycetes—are able to reduce soil nitrates to nitrites; and certain fungi and special bacteria are able to reduce nitrates to ammonia in obtaining their supplies of oxygen. In a cultivated soil, this does not necessarily involve a loss of nitrogen, but rather a transformation of soil nitrogen, because both nitrites and ammonia are usually acted upon by nitrifying bacteria, as well as assimilated by other micro-organisms.

Denitrification. Under anaërobic conditions, or when the air supply is deficient, certain bacteria (denitrifiers) are able to reduce soil nitrates and nitrites to oxides of nitrogen (NO_2 and NO) and to elemental nitrogen (N_2), in which forms the nitrogen passes into the atmosphere. The oxygen liberated is used by the bacteria to break down cellulose. This reduction process is called "denitrification," and it takes place in the absence of free oxygen and in the presence of an abundance of organic matter. The ultimate effect is injury to plants, resulting from a loss of nitrogen.

A distinction is made between nitrate reduction and denitrification, in that the latter process gives rise to oxides of nitrogen and free or elemental nitrogen.

BACTERIA THAT FIX AIR NITROGEN

Soils may gradually become enriched in nitrogen through the action of certain groups of nodule-forming bacteria which have the ability to fix atmospheric nitrogen. These bacteria form nodules on roots of leguminous plants like clovers, alfalfa, peas, and beans (Figs. 17 and 18). Intimate association of two dissimilar organisms, such as nodule bacteria and clover plants, is called "symbiosis"—hence the term *symbiotic fixation of nitrogen.* Soils may also become enriched in nitrogen through the activity of nonsymbiotic, or free-living, nitrogen-fixing bacteria.

Symbiotic fixation of nitrogen. Fixation of atmospheric nitrogen by bacteria within nodules on roots of legumes was definitely established by Hellriegel and Wilfarth (Ger.) in 1886. They also

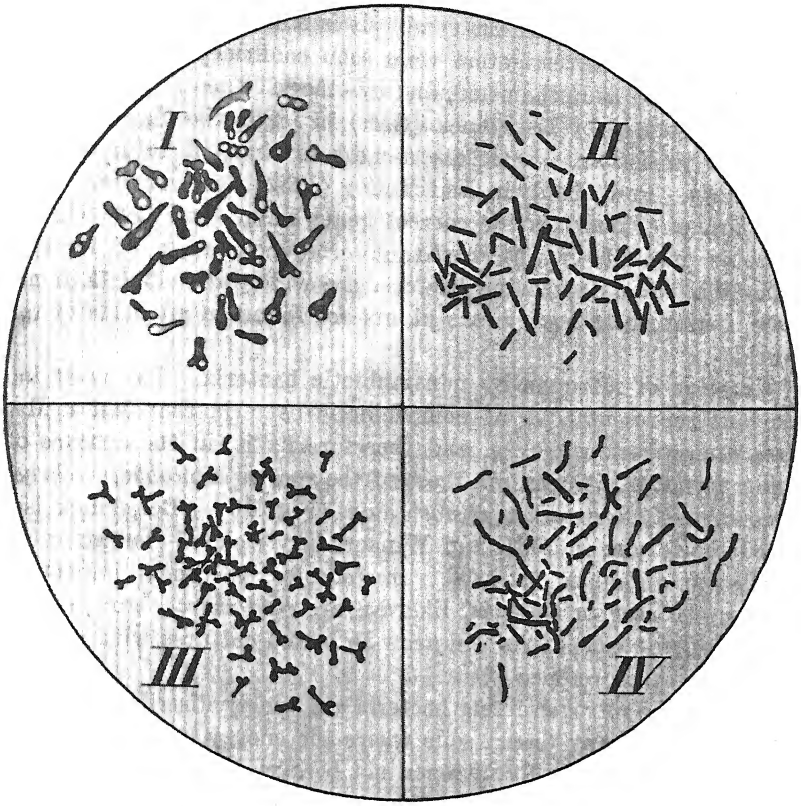


Fig. 17. Different forms of legume bacteria: I, alfalfa; II, red clover; III, vetch; and IV, locust.

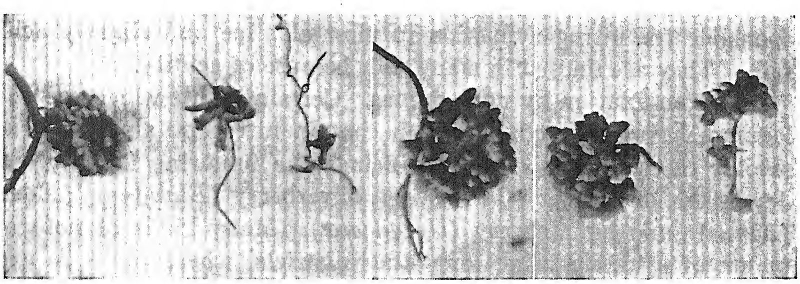


Fig. 18. Nodules formed by symbiotic nitrogen-fixing bacteria. The first three to the left are alfalfa nodules; the three to the right are vetch nodules.

established the fact that the symbiosis is mutually beneficial. The results of these investigators were soon confirmed by Lawes and Gilbert (1890) at Rothamsted, and by others. The causative organism was isolated by Beijerinck (Ger.) in 1888, who classified it as *Bacillus radicicola.* Later its name was changed to *Bacterium radicicola.* Fred, Baldwin, and McCoy (1932) have concluded that *Rhizobium* (Frank) is the correct genus name, and have classed rhizobia into 15 groups, based on cross-inoculation of legumes (Ch. 19). Nodule-forming bacteria are widely distributed in nature, inasmuch as leguminous plants are found in all parts of the world.

Fixation of nitrogen by nonsymbiotic bacteria. The most important representatives of nonsymbiotic bacteria that can utilize free atmospheric nitrogen, and therefore fix it, in the absence of other forms of nitrogen are those of the species *Azotobacter chroococcum* and *Clostridium pastorianum* (Fig. 16). Beijerinck isolated the former in 1901, and Winogradsky isolated the latter, an anaërobic organism, in 1893. *Azotobacter,* the most important group, are aërobic bacteria, likewise are *Radiobacter* and others. The *Clostridium* bacteria can grow in mixed cultures with aërobic bacteria in the presence of air.

Free-living nitrogen-fixing bacteria are widely distributed in nature, even in many desert soils where the energy required is supplied by algæ. They fix nitrogen not because of necessity, but because they have the power, for they will use available combined nitrogen in preference to taking it from the air and fixing it within their cell bodies. They derive their energy mainly from soil carbohydrates. Azotobacters are probably the organisms principally responsible for nitrogen fixation in most alkaline and slightly acid soils. They are limited in many soils because of acidity.

Nitrogen-fixation by nonlegumes. Certain plants which are not legumes have root nodules which contain nitrogen-fixing bacteria similar to the rhizobia. These include the following kinds: New Jersey tea, or redroot (*Ceanothus*); silverberry (*Elæagnus*); alder (*Alnus*); and buffaloberry (*Cycadaceæ*). Many kinds of natural plants of arid, semiarid, and other districts, where the soils are poor in organic matter and nitrogen, grow in close association with nitrogen-fixing agents, such as legumes (as lupines in association with western pines), nodule-forming bacteria, algæ, and mycorhizal fungi.

On the leaves of certain tropical plants—Myrsinaceæ and certain Rubiaceæ—a symbiosis has been found similar to that of rhizobia and legumes. These bacteria invade the leaf tissue through the stomata and establish themselves in spherical glands which are conspicuous as blisters on the surface of the leaves. They have the power of fixing atmospheric nitrogen.

THE NITROGEN CYCLE

Soil micro-organisms make possible a nitrogen cycle. The original source of all nitrogen is the atmosphere. But as plants can-

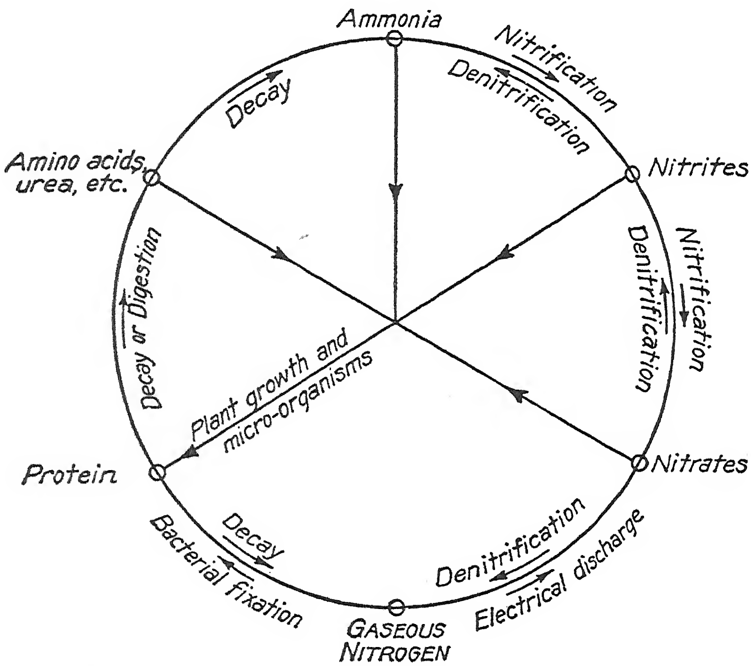


Fig. 19. The nitrogen cycle in nature. (After Allison, F. E.)

not use nitrogen in its free or molecular form, nature has provided means whereby this inert nitrogen may be fixed in forms suitable for plants. A small quantity is also fixed naturally by electrical discharges in the atmosphere, amounting to an average of about 7 or 12 pounds of nitrogen per acre annually, as ammonia and oxides of nitrogen.

The nitrogen that is absorbed and assimilated by higher plants

and micro-organisms becomes locked up in complex insoluble organic compounds, and is ultimately released, through decomposition effected principally by bacteria and fungi, usually in such forms as to allow its use again by higher plants. Thus nitrogen goes round and round, as it were, in a cycle, existing for a time as gas, converted into forms suitable for plants, locked up in organic compounds, and released again for the sustenance of plants. Allison's (F.E., 1926) conception of this cycle is shown schematically in Figure 19.

In this cycle there are involved two principal processes of vital importance in crop production: (1) fixation of air nitrogen for use by plants; and (2) the conversion of the nitrogen that becomes locked up in plant and animal substances into simpler compounds, in order to make possible its use again by plants. When we consider that both processes are dependent on soil micro-organisms, we can appreciate the important part these tiny organisms take in the maintenance of plant and animal life.

OTHER SOIL ORGANISMS

Sulphur bacteria. Certain soil bacteria derive their carbon from carbon dioxide of the air and their energy from oxidation of sulphur and its compounds. In the process of decay, the sulphur of protein compounds is converted mostly into hydrogen sulphide on which sulphur bacteria thrive, oxidizing it into sulphuric acid and at the same time storing some sulphur within their own bodies—as, for example, in *Beggiatoa* bacteria.

In ordinary soils, the sulphuric acid formed may act on insoluble calcium phosphate and render it available to plants. Oxidation of sulphur in black-alkali soils makes possible the use of sulphur in the reclamation of such soils. (Ch. 4.)

Iron bacteria. In all soils are present certain bacteria that derive their energy for assimilation of carbon by oxidizing iron from the ferrous to the ferric form. It is doubtful whether they are in any way useful in soil fertility. On the other hand, they may prove to be extremely troublesome in water-supply systems by clogging pipes with iron which is deposited by them as minute tubes of ferric iron oxide.

Fungi. The importance of soil fungi—yeasts, molds, and actinomycetes—is being increasingly recognized. These organisms are present in soils in very great numbers, being most abundant in the

surface layers. Forest soils usually contain a high proportion of fungi and a low proportion of bacteria. By plate counts, Jensen (Den., 1931) has found from 24,300 to 46,000 fungi to a gram of acid soil material rich in organic matter.

Fungi are probably the most important factor in decomposition of the cellulosic matter of plant residues. They are also active in decomposition of organic nitrogenous compounds and in the formation of ammonia.

Many soil fungi are disease-forming, and some are among the most destructive parasites of agricultural plants.

Various species of fungi live symbiotically with higher plants. This symbiotic fungous growth on plant roots is called "mycorrhiza." The mycorrhizal relationship is not understood; but with forest trees, particularly, there seems little doubt of its vital importance.

Algæ. Algæ, which are chlorophyll-containing micro-organisms which obtain most of their energy from sunlight, occur in practically all soils and fresh waters, representing many species. It is known that algæ of some species live in symbiotic association with nitrogen-fixing bacteria and that they supply energy to azotobacters. According to Allison and Morris (1930), blue-green algæ (Nostoc, genus) are probably the most important nitrogen-fixing agents in many soils. Fletcher and Martin (1947) found that rainfall-induced crusts on desert soils, formed by algæ (including Nostoc) and molds, contain as much as 300 to 400 percent more nitrogen than the soil layers immediately below such crusts.

Fauna. Protozoans, the smallest and most primitive of animals, constitute the most abundant animal population of soils. Cutler and co-workers (Eng., 1920) have shown that the principal causative agents of bacterial fluctuations in soils are active amœbæ (protozoans). According to Luck, Sheets, and Thomas (1931), some of these organisms feed on living bacteria, some on other protozoans, and others devour dead micro-organisms. Research has shown that protozoans are probably important soil organisms. The presence of these tiny animals generally stimulates fixation of nitrogen by azotobacters.

In addition to protozoans, there are rotifers, nematodes, worms, and insects which live in soils, affecting directly and indirectly soil processes and plant growth. The relation of soil micro-organisms to soil fertility is discussed in Chapter 19.

SUGGESTED REFERENCES FOR READING

RUSSELL, E. J. Plant Nutrition and Crop Production. 1926.
WAKSMAN, S. Principles of Soil Microbiology. 1932.

REVIEW QUESTIONS

1. What constitutes the vital part of soils? Explain.
2. Discuss the relationship, in general, between soil micro-organisms and living things and dead matter.
3. Through the use of a diagram or sketch, illustrate the distribution of micro-organisms in a soil on which clover and timothy plants are growing.
4. Explain why a layer of oat straw on the ground surface may stunt the growth of young corn plants and cause yellowing of the leaves.
5. In a depression on a field of young barley, standing water caused the plants to turn yellowish. Why?
6. In the management of a productive silt loam, for example, which are the important microbial activities that one should consider—ammonification, nitrification, nitrate reduction, denitrification, and nitrogen fixation—and why?
7. What is the most important fact shown by the nitrogen cycle?
8. What lesson may we learn from soil micro-organisms, so far as efforts are concerned?
9. What may be regarded as the seat of the microbial activities in soils, humus, or organic matter? Why? What is the economic significance of this fact, in relation to soil productivity?

CHAPTER 6

THE MODERN CONCEPT OF SOILS

The consideration of soils as a subject worthy of a place among the natural sciences has been made possible through the discovery of the three following general facts about soils: (1) Soils are something more than simply the ground or geologic materials that result from rock weathering. (2) As definite earthy bodies, soils have developed from deposits of unconsolidated geologic materials through the action of definite forces. (3) The natural forces concerned have caused the development of distinguishing soil characteristics which, in turn, has made possible the discovery of natural order in soils. These facts were established by Dokuchaev, a Russian scientist, in 1879.

Old v. modern concepts. The ancient concepts regarding soils—*the ground, the earth, the land,* and *the soil*—pertained to one and a common medium in which plants anchored themselves in growth. In the course of time primitive and ancient husbandmen found that in some places the ground differed in its fruitfulness, hence the very early attempts that were made to classify land areas on the basis of utility or crop adaptation (Ch. 1).

The term "soil" is of Roman origin (from Latin term, *solum*), which meant loose earthy material in which plants grew. Hence, "the soil" is a Roman concept which had the same meaning as "the earth" or "the ground." In the development of scientific geology following the Renaissance, the term "soil" acquired another meaning, namely, geologic material that results from disintegration and decomposition of country rocks. The Roman concept of soil centered on inert material that constituted the ground, the geological concept of soils centered on geologic materials alone, but the modern concept of soils centers on natural, dynamic, earthy bodies which have developed consequent to the action of soil-forming forces on deposits of loose geologic materials.

This development represents various stages of soil formation.

Beginning stages are represented by recent depositions of alluvium exposed to soil-forming forces, and by soil mantles on steep slopes, where erosion has not allowed the development of soil characteristics much beyond incipient stages. These are young soils. Well-drained, level, and slightly rolling lands and others, as water-saturated areas, where soil-forming forces operate without hindrance, are characterized by mature soils—that is, soils with well-developed or clearly defined features. Further, on some very old deposits of soil-forming materials, where the effects of weathering and soil-forming forces have advanced beyond well-developed stages to deteriorated soil conditions (indicating equilibrium with environmental forces), post-mature soils may occur.

SOIL GENESIS

Origin of soil-forming materials. The parent materials of mineral soils originate through the disintegration and decay of country rocks, effected by mechanical and chemical processes, which, collectively, is *rock weathering*. The chemical processes involved include solution, hydrolysis, carbonation (CO_2), oxidation, reduction, and clay formation. In addition to the lesser factors (plants and animals), the principal weathering agents are as follows:

Heat. Through sudden temperature changes, as in arid and semiarid regions, exposed rock masses are broken and rounded off.

Frost. Through the action of freezing water, rocks are cracked and broken into pieces.

Wind. Winds, carrying sand and dust particles, effect abrasion.

Ice. Through the grinding action of glaciers, rocks are broken and even converted into rock powder and flour.

Water. Water may act by wearing, dissolving, and in effecting chemical changes. It is a most active agent in rock decay and in the formation of secondary minerals.

Gases. Carbon dioxide and oxygen are very active weathering agents in both rock decomposition and formations of secondary minerals.

Specific products of rock weathering. The residual material that originates from the weathering of a granite, for example, is vastly different from the parent rock. It consists of loose material made up of particles of various sizes (gravel, sand, silt, and clay), including unaltered particles of the parent rock and particles of secondary minerals formed during the process. While these changes take place, salts are formed, originating through chemical actions like hydration, oxidation, and carbonation.

One of the most important processes in rock weathering was thought to be *kaolinization,* the conversion of feldspars into kaolin (clay mass), according to the following reaction:

$$\underset{\substack{\text{Orthoclase}\\\text{(Potash feldspar)}}}{2KAlSi_3O_8} + \underset{\text{Water}}{2H_2O} + \underset{\substack{\text{Carbon}\\\text{dioxide}}}{CO_2} = \underset{\substack{\text{Kaolinite}\\\text{(True clay)}}}{Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O} + \underset{\text{Quartz}}{4SiO_2} + \underset{\substack{\text{Potassium}\\\text{carbonate}}}{K_2CO_3}$$

It has been found that the "kaolinite" is mostly colloidal, and that probably only a small part is definite mineral, most of it being a varying mixture of hydrous oxides of aluminum and silicon (Ch. 4). The residual clayey soil-forming material, which consists largely of this mixture (with kaolinite), has been called "siallite" by Harrassowitz (Ger., 1926); it corresponds to the clay mineral now designated as "halloysite." Accordingly, the conversion of rock minerals or mineral soil particles into this secondary product, in which the alumina-silica ratio is about 1 to 2, may be called "siallitization." This is distinctly a decomposition process, in that the residual soil-forming materials are different from the original rocks or rock minerals.

Rock weathering illustrated. The relation between the original rocks and the residues that result from weathering may be shown, in case of granites, as follows:

FROM GRANITES TO SOIL-FORMING MATERIALS

Granites		Specific Products of Weathering	Accumulated Residues
Mineral Composition	Principal Elements Composing Rock-forming Minerals		
Feldspars..........	K, Na, Ca, Al, Si, O	Gravel, sand, silt, clay, and salts	Sandy-loam and loamy materials
Quartz............	Si, O		
Micas.............	K, Na, Ca, Mg, Fe, Al, Si, O		
Hornblende........	Na, Ca, Mg, Fe, Al, Si, O		
Pyrite............	Fe, S		
Apatite...........	P, Ca, F, O		

Losses in rock weathering. In rock weathering, the components of the original rocks suffer considerable losses, principally through the action of water. Running waters carry away soluble salts in solution and solid particles in suspension. The salts are carried to the oceans where they become the "salt of the sea," while the solid matter is deposited as sediments along streams and in bodies of water.

A part of the total loss in rock weathering is offset by gains of water, oxygen, and carbon dioxide. In some cases the gains may

exceed the losses. In the weathering of limestone, exceedingly heavy losses of carbonates occur. The relative losses and gains in the weathering of an igneous rock may be shown by the following comparative chemical compositions of a micaceous granite, of the same rock partly decomposed, and of the residual soil-forming material.

CHEMICAL COMPOSITION OF GRANITE AND ITS WEATHERED PRODUCT[1]

Chemical Constituents Expressed as Oxides	Fresh Granite	Granite Partly Decomposed	Residual Soil-forming Material
	Percent	*Percent*	*Percent*
SiO_2, silica	69.33	66.82	65.69
Al_2O_3, alumina	14.33	15.62	15.23
Fe_2O_3, ferric oxide	——	1.88	4.39
FeO, ferrous oxide	3.60	1.69	
MgO, magnesia	2.44	2.76	2.64
CaO, lime	3.21	3.13	2.63
Na_2O, "soda"	2.70	2.58	2.12
K_2O, "potash"	2.67	2.04	2.00
TiO_2, titanium oxide	Undet.	Undet.	0.31
P_2O_5, "phosphoric acid"	0.10	Undet.	0.05
Loss on ignition	1.22	3.27	4.70

Accumulation and deposition. The residues that result from rock weathering constitute the soil-forming materials, though not necessarily the *parent* materials, owing to the fact that much residual material does not become parent material of soils until after it is transported and deposited elsewhere. When soil-forming materials remain in place or accumulate over the rocks from which they originate, they are described as "residual," or materials *in situ*. However, it is a common thing for the loose soil-forming materials to be carried away by natural agents and deposited in different places, forming *marine* deposits, *alluvial* deposits through the deposition of sediments by running water, *lacustrine* deposits through the deposition of sediments in glacial lakes, *glacial drift*, *loess* through the deposition of wind-borne material, and *colluvial* deposits through the action of gravity, as on talus slopes. In addition to these, there are deposits of *cumulose* material which consist of the remains of partly decayed plants, as in some marshes.

In the preceding paragraph are named the various kinds of geologic deposits on which the soil-forming forces act and from which, in consequence, many kinds of soils develop. We shall first

[1] CLARKE, F. G. THE DATA OF GEOCHEMISTRY. Dept. Int. U. S. Geological Survey Bull. 770, p. 490. 1924.

consider briefly these deposits, and then give our attention to the soil-forming factors and to soil development in general.

Residual deposits. There is a close relation between the kind of rock and the character of the residue left on weathering. Commonly, the residue from granite weathering, as has been indicated, is loamy in character; from sandstone, sandy; and from limestones, shales, and slates, it is silty and clayey.

Soils that develop from residual materials originating from various kinds of rocks may show different characteristics. In some places, however, two or more different residual materials have given rise to soils that have like characteristics, owing to the fact that they have been subjected to the same soil-forming forces. Conversely, different soils may develop from the same kind of geologic material in consequence of the action of unlike or unequal forces and of difference in time through which the forces have acted.

Sedimentary deposits. Sedimentary deposits, particularly the marine and alluvial, may form from materials that originate from various sources, including areas in which the upland soils are already fully developed. Such deposits have given rise to large areas of agricultural soils, some of which are the richest in the world.

Immense quantities of sediment have accumulated in preëxisting lakes and seas, and have been and are accumulating in present bodies of water. It has been estimated that the Mississippi River, for example, in addition to depositing alluvium along its course, carries into the Gulf of Mexico each year a quantity of sediment equal to a pile of sand and mud 1 mile square and 288 feet deep.

The regions in which marine deposition takes place most actively are those of the continental shelves. Here the coarse materials are dropped near shore, and the finer materials are carried farther out and deposited in deep water. The soils of the Atlantic and Gulf Coastal Plains and of the valley of the Red River of the North, respectively, are good examples of soils that have developed from deposits of marine and glacial-lake sediments.

Flood plains (river flats and deltas) are typical illustrations of alluvial deposits. The alluvium deposited by streams consists of soil materials that had been eroded from upland areas of different kinds of soils. On flood plains, it is common to find the coarser-textured soils near the stream beds and the finer-textured soils farther back where the fine particles had settled out in quiet waters.

The flood plains of the Mississippi River alone cover an area of about 30,000 square miles.

Glacial drift. Materials deposited by glaciers, taken collectively, is known both as "glacial till" and "glacial drift," including those deposits which constitute outwash plains. Such superficial deposits extend over 8,000,000 square miles of northern Europe, North America, and large areas in Asia, and they occur also in the Southern Hemisphere. They were laid down many thousands of years ago by different continental ice sheets. So far as North America is concerned, the Kansan Till, the first, was laid down not less than 400,000 years ago; and the Wisconsin Till, probably the last, from 20,000 to 50,000 years ago. These ice sheets were large enough to slide over the mountains of New England, and some of them moved southward as far as what is now southern Illinois.

The features of a glaciated country are rolling lands, scattered boulders of all sizes and kinds, low ranges and hills, and numerous lakes. Soils formed from glacial materials differ widely in character and agricultural value, ranging from sandy to heavy silt and clay loams. Some are very stony and others have poor natural drainage.

Loess. Owing to the fact that loess consists of wind-borne material, it is extremely fine in texture. Other characteristics include yellow or buff color and angularity of individual particles. Loess deposits lack stratification, have the ability to retain vertical walls, have a high degree of porosity, and contain small capillary tubules which seem to have been occupied by rootlets. Fossils found in some deposits are of land animals, thus indicating the manner of origin. In Europe and America loess is associated with margins of great ice sheets of the glacial periods. Many soils of the Mississippi Basin have formed from loess, and immense deposits occur in Asia, especially in China. Soils derived from loess are free from stones and are very productive.

Colluvial deposits commonly consist of coarse materials and are usually stony and have steep slopes, making them unsuited for cultivation.

Cumulose deposits develop in comparatively shallow bodies of water, especially those which occur in temperate and cold, humid regions. When the aquatic plants that grow in these shallow waters die, their leaves, stems, and roots settle to the bottom, there accumulate, and ultimately form peat. Often floating bogs de-

velop, which thicken and in time settle to form peat beds. When more or less mineral matter becomes mixed with peaty material and the whole mass becomes well advanced in decay, the deposit is called "muck." Peat and muck are found in marshes and swamps.[2] Many peat and muck areas, when properly drained and fertilized, have been made into excellent agricultural lands.

Organic soils. In the study of soils, we find not only *mineral* soils, but also soils of organic origin which have developed from peat and muck deposits.

FACTORS OF SOIL DEVELOPMENT

The features or qualities that predominately characterize soils as distinct natural objects and that differentiate the various classes in a scientific classification of soils invite consideration of the factors that cause the development of those distinctive soil characteristics. Most of the factors may be grouped into four classes: *climatic* (percolating precipitation water and heat), *biotic* (plants, or vegetation, and other organisms), *edaphic* (drainage and ground water), and *topographic* (ground-surface relief). There are also the factors of *time,* through which the active soil-forming agents act, and *parent material.* The important active agents are precipitation water, heat, plants (vegetation), and ground water. Other factors are passive, including drainage conditions, topographic relief, time, and parent material.

Climatic factors. There is a very close relationship between the great soil belts of the world and climates. If one were to fly from the arctic region of North America southward through the eastern part of the United States to the humid tropics, through humid regions with increasingly higher annual temperatures, he would pass over land areas characterized by upland soils that have striking distinguishing characteristics, as follows:

Tundra soils of the arctic region—shallow soils, accumulation of plant remains (mosses, etc.), subsoils usually frozen year long.

Gray and gray-brown forest soils of humid, cool, temperate regions—soils with considerable organic matter, acid, yellowish-brown subsoils, high clay content especially in subsoils, definite layer development (topsoils and subsoils). (Fig. 21.)

2 Marsh commonly means level areas that are saturated with either salt or fresh water and on which grasses grow, whereas swamps are usually understood to mean low, wet, spongy land in fresh-water regions and on which trees grow, including tamaracks, cedars, and cypresses.

Red and yellow forest soils of humid, warm temperate region—soils rather low in organic matter or humus, strongly leached, acid, rich in clay, definite layer development. (Fig. 21.)

Reddish-brown and yellowish-brown forest soils of the tropics—laterites and lateritic soils with silica leached out, accumulation of claylike materials in topsoils, iron crusts and hardpans, somewhat acid, layer development.

And if one were to wing his way westward across the United States from the eastern humid part, say from Philadelphia, Pa., to a desert area in northern Wyoming, through a cool temperate region of diminishing annual rainfalls (Fig. 20), he would pass over land areas of different kinds of upland soils, as follows:

Gray-brown forest soils, described in the previous paragraph.

Dark-colored soils of true-prairie areas (humid region)—soils rich in humus, topsoils slightly acid, subsoils not acid, high clay content especially in subsoils, definite layer development.

Deep black soils of grasslands (subhumid climate)—soils very rich in humus, topsoils not acid, accumulations of carbonate of lime in the subsoils, little layer development.

Chestnut-brown soils of short-grass plains (still lower annual rainfall)—soils with less humus than prairie and black soils, alkaline, accumulations of lime carbonate near surface, slight layer development.

Light-brown soils of short-grass semidesert plains which may border desert areas (Fig. 21)—soils low in organic matter, calcareous throughout, very slight or no layer development.

Gray soils of the desert, low in organic matter, low clay content, alkaline-calcareous throughout, no layer development.

If landing were on the desert immediately west of Big Horn Mountains, northern Wyoming, and if one were to ascend the western slopes of these mountains, he would see soil belts similar to those he would cross in returning to Philadelphia, namely, gray desert, light-brown semidesert, chestnut-brown, deep black, prairie, and at elevations of 8,000 and more feet, gray and grayish-brown forest soils.

Similar relationships of climates to soils occur in other parts of the world, but not necessarily the same combinations of rainfalls and temperatures as previously described. In European Russia, for example, from north to south, zones of diminishing annual rainfall and increasing temperature are coincident. If one were to go from

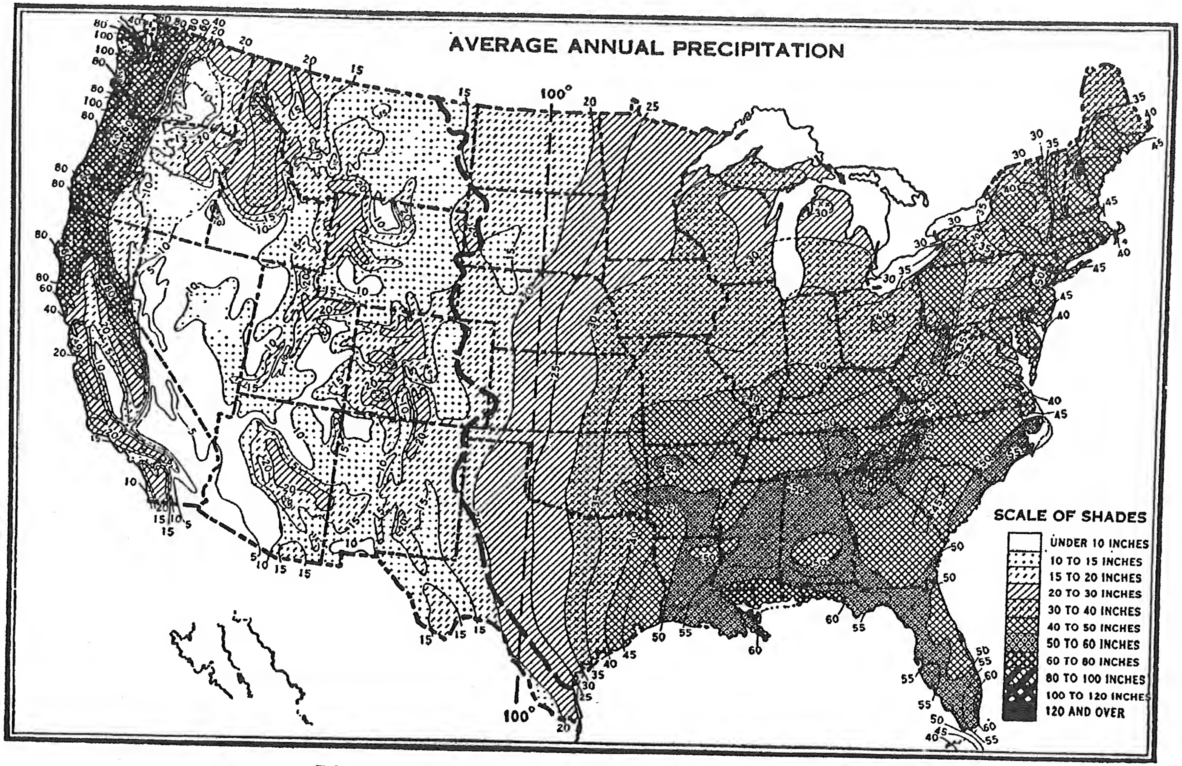


Fig. 20. Annual rainfall of the United States.

the Arctic Ocean through Archangel south to the Caspian Sea, he would cross the following zones: (1) a tundra belt; (2) a wide zone, to about the latitude of Moscow, the uplands of which comprise acid, gray and grayish-brown forest soils; (3) black-earth soils of grasslands (steppes); (4) chestnut-brown soils of steppes; and (5) brown, dry-steppe soils. Associated with the latter belt are gray desert soils.

Predominant actions of climatic forces. In the great soil belts of the world, factors other than rainfall and temperature have also operated conjointly. Native vegetation, for example, played an important role. In general, the two climatic forces in themselves have produced certain dominant effects. To illustrate: In humid regions, percolating rain water has leached the basic chemical elements from upland soils, with the consequent development of acid soils. In contrast, no acid upland soils have developed in arid locations. In areas where climates range from arid to subhumid, restricted soil leaching has resulted in the accumulation of carbonate of lime through the soil mass in the desert and semidesert areas, and in the chestnut-brown and black grassland soils at depths increasing with increase in annual subhumid rainfall.

Further, in desert and semidesert areas, also under frigid conditions, comparatively little clay forms in the soils; whereas in areas having the same annual temperature, other conditions remaining the same, clay formation increases with increase in annual rainfall. And in areas having the same annual rainfall, clay formation increases with increase in average annual temperature.

Another important effect of climatic forces is the development of major layers in well-drained upland soils, commonly known as topsoils and subsoils, technically called A horizons and B horizons. Clearly defined topsoils and subsoils characterize soils of well-drained upland areas in humid regions; whereas under similar conditions in areas of low rainfall, there are no such major layers or only slightly developed layers. It is important to bear in mind that the presence or absence of soil horizons does not necessarily indicate well-developed, or mature, soils, on the one hand, or undeveloped, or immature, soils, on the other. A soil on an area of well-drained, level or gently rolling upland in an arid location, even without any perceptible horizon development, may be as well developed for its situation as a soil on an area of well-drained level or gently rolling upland in a humid location, and which has sharply

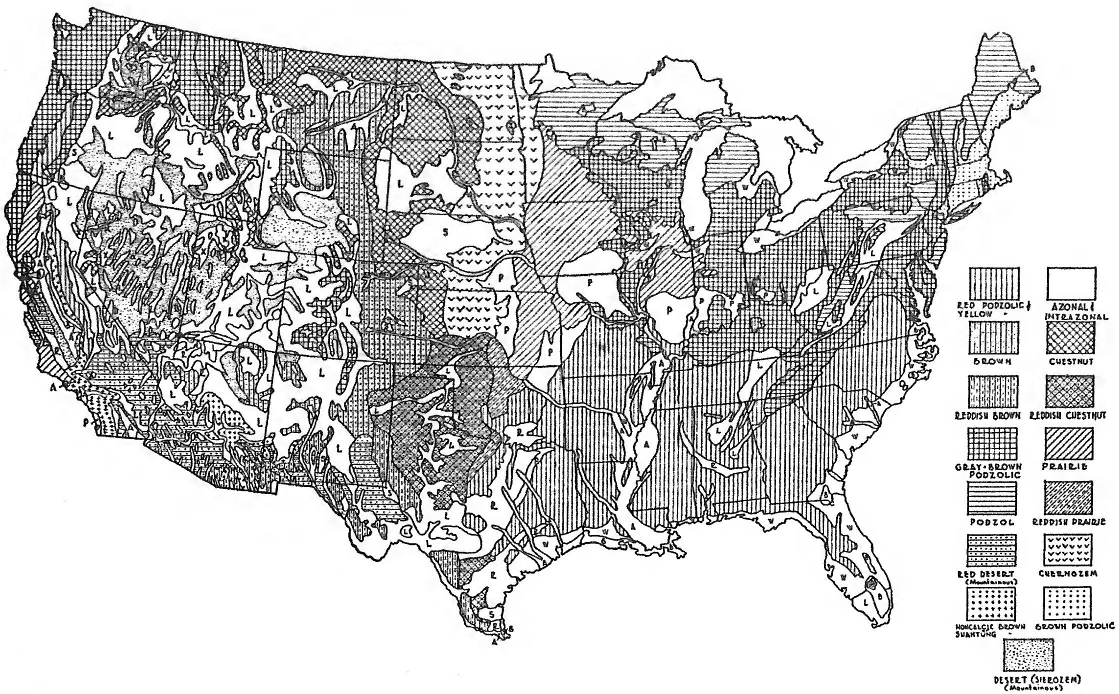


Fig. 21. Land divisions in the United States based on great soil groups. (After U. S. Dept. Agr.) Also, L, Lithosols and shallow soils. A, Alluvial soils. B, Bog soils. R, Rendzinas. S, Sands. X, Alkali soils. P, Planosols. W, Wiesenbodens, ground-water podzols, and half-bog soils.

defined topsoil and subsoil. Each soil, in all its distinctly defined characteristics, may reflect equally the unrestricted and effective action of all the soil-forming forces that are peculiar to its environment. Logically, any soil, whether on well-drained level or gently rolling upland or formed in a depression water-saturated the year round, whose distinguishing features reflect unhampered and effective action of the soil-forming forces to which it has been subjected, may be described as well developed or mature.

In previous paragraphs, references are made to cross-country and altitudinal climates and to various combinations of the climatic forces in soil development. It is important to consider also annual rainfalls of different types, such as (1) rather uniform distribution through all the months of the year, as in humid eastern United States, (2) the larger percentage of the rainfall occurring in summer months, as in central United States, (3) low summer and high winter distribution, as on the Pacific coast, and (4) winter distribution in protracted, low-intensity rains and summer distribution as local showers and short-time thunderstorms, as in southwestern United States. Rainfalls of these four types operate in soil formation conjointly with temperatures ranging from low to high.

Biotic factors. Of the biotic agents of soil genesis, plants, in associations generally called vegetation, are the most important. Vegetation is a dependent factor, because it is determined by climate. In its complex role, vegetation aids the infiltration of rain water, contributes organic matter and humus, and, affording protection to the ground surface against erosion, especially on slopes, allows the development of soils. Grass vegetation may predominate over climatic factors in the development of certain soil features. On the true-prairie areas of east-central Illinois, for example, under a humid climate favorable for the growth of forest trees, quite different soils have developed than under forest cover in the same climate to the east.

Organic litter matted on the ground, in various stages of decay, is a potent factor of soil genesis, operating conjointly with climatic forces. One of the commonly observed effects of organic matter on soils is shown in their dark colors—black, brown, and shades of colors. Another important effect is indicated by acid soils. In the same humid climate, soils developed under forests are more acid than those under grasses, as on prairies, largely because the rain

water that passes through the leaf mat or mold on the forest floor has more effective dissolving and leaching power than that which passes through organic matter accumulated under the prairie grasses.

As regards the development of acid soils under forest cover, *kind of tree* is an important factor. Generally, most acid soils have developed under spruces, firs, and pines; not so acid soils under trees like oaks and ashes; and less acid soils under maple, walnut, hickory, and beech trees. Coville (1913) published some significant data regarding the acidic effects of fallen forest leaves in terms of tons of limestone required to neutralize the acids developed on an acre covered with a 6-inch, compact layer (250 tons). White-oak leaves required 25 tons of limestone; maple 22; Virginia pine 22; red oak 16; and tulip-tree leaves 14 tons. Maple leaves on the forest floor may rot rapidly and reach an alkaline stage within a year; oak leaves may remain acid for several years; and pine needles may remain acid for many years. From all sources, Salisbury (Eng., 1922) compiled the following average percentages of calcium contained in some forest leaves: beech 2.46 percent; birch 2.3; chestnut 2.2; oak 1.7; pine 0.99; and heather 0.44 percent.

Edaphic factors. The edaphic factors of soil genesis refer to physical ground conditions that influence soil development, principally as regards natural internal drainage and ground water (p. 31).

Drainage, whether good or poor, may be indicated by the rates of infiltration of water into the ground and of percolation (p. 36). In previous paragraphs, references are made to the importance of good internal drainage in the formation of well-developed, or mature, upland soils. Poor drainage restricts the action of certain soil-forming forces, especially those of climate, conjointly with vegetation. Only under conditions of good drainage can these soil-forming forces exert their full influences. Internal drainage—good, fair, or poor—and depth to ground-water table are closely related to features that differentiate soils of some family groups, for example, named in order from good to poor drainage, *Miami, Crosby,* and *Brookston* soils, in the Indiana-Ohio region, also *Orangeburg, Dunbar,* and *Portsmouth* soils, of the Atlantic Coastal Plain.

Ground water, which is closely associated with drainage, refers to saturated conditions, where the water table remains at or near the ground surface, also, where there is periodic rising and falling of

the water table. Even in such locations, well-developed soils have formed, whose clearly defined features reflect unrestricted influences of the soil-forming forces that are peculiar to such situations. Soils influenced by ground water include those of Bog and Half Bog classes (peat, muck, peaty, fen, moor) and meadow soils, mostly under humid and subhumid climates; alkali soils of dry regions and other generally scattered saline soils; and ground-water podzols and laterites of warm temperate and tropical regions.

Topographic relief. The fact that definite effects of the climatic forces, acting with vegetation, may best be observed in the soils of naturally well-drained uplands, implies that on steep slopes, other conditions remaining the same, soils may be shallow and poorly developed, they may represent incipient stages of development (young soils), there may be accumulated residues from rock weathering with no trace of any soil development (which deposits may be called collectively and geologically the *soil mantle*), or there may be simply fresh and partly weathered masses of rock fragments (so-called *skeletal soils*). On sloping areas between level lands and steep slopes, the influence of surface relief may be reflected largely in depth of soil (topsoil plus subsoil) and in the amount of accumulated soil-forming mineral materials and organic matter. The degree of influence of ground-surface relief in soil development is determined by the rate of removal of soil materials by surface runoff, or, under natural conditions, through normal erosion. In this, protective vegetation plays a most beneficial role (p. 105).

The time factor. The terms "young," "mature," and "postmature," as applied to soils, imply time through which soil-forming forces have acted. These terms also imply the development of young soils into mature soils, and the ultimate decline of mature soils. In many soils, the degree of development of distinguishing features probably has been determined by the time factor. In a given climate, the young soils on an area of recently deposited alluvium and soils in postmature stages on a very old flood plain reflect wide variation of time in soil formation.

Parent material. Obviously, many characters or qualities of young soils are due to internal factors, which, collectively, may be designated as parent material. But in time, in most soils, the external forces predominate over the internal factors in the development of distinguishing soil characteristics. This is what Dokuchaev (U.S.S.R.) discovered in the black-earth soils (chernozems, pp. 102, 104) which embrace extensive areas of his country. He observed

that these deep, black soils covered country rocks of various kinds—granites, limestones, chalk, siliceous clay, and sandstones—yet the major characteristics were identical; and he concluded that these features were due to climatic forces, acting conjointly with vegetation (grasses of Russian steppes).

In some well-developed soils, certain characteristics are inherited from the parent materials. In the *Penn* soils of eastern United States, for example, the Indian-red of the topsoils and purplish colors of subsoils have been imparted by weathered shales and sandstones of the same colors. Among other qualities imparted to soils by parent materials and which external forces may not efface, are implied in the following concepts: mineral soils, organic soils, sand and sandy soils from sandstones, clayey soils from shales, and gravelly soils from gravelly outwash materials. But such implied characters, which indicate the very nature of parent materials themselves and which therefore cannot be regarded as having developed in consequence of soil-forming forces, have much the lesser importance in natural, or scientific, classification of soils. The validity of such classification, it is important to remember, rests in distinguishing soil characteristics that have resulted from soil-forming forces acting externally to the inherent nature of parent materials.

SOIL-FORMING PROCESSES

Although there are two major steps in the transformation of country rocks into soils—first, the origination and accumulation of geologic soil-forming materials; and second, the formation of soils—it is not to be inferred that all the rock-weathering processes stop when soil formation begins. In fact, climatic and biotic forces influence rock weathering; and rock-weathering processes operate also in soil formation. By definition, the concept *rock weathering* extends, as it were, from rocks to the resultant altered residues; whereas, by definition, the concept *soil formation* extends from the accumulated geologic residues that result from rock weathering to soils as distinct resultant objects having distinguishing characteristics which allow a natural classification of them. The striking features of the soils that characterize the climatic belts and other areas of the world clearly indicate, not weathering, although weathering processes continue, but rather the dominant effects of climatic, biotic, and other natural forces, whose conjoint actions effect soil-forming processes, such as *podzolization, laterization, calcification, salinization, desalinization, gleization,* and *peat formation.*

Podzolization. In humid regions, soils are leached of their basic elements, become acid, and proportionately more iron and alumina (Al_2O_3) than silica (SiO_2) are carried down from topsoils to subsoils. This is *podzolization,* which tends to the ultimate development of bleached soils called podzols.[3] Thus, generally, we speak of podzolized and podzolic soils. This soil-forming process is widespread in temperate and tropical regions. Here the distinctly acid soils, which have formed under forests of conifers and broad-leaved trees and also under heath (ericaceous shrubs), indicate effective podzolization, a deteriorative process.

Under acid conditions, clays tend to disperse and dissolve, likewise organic matter and humus. Aqueous solutions that filter down through the ground cover of leaf mold and which contain humic acids or acid organic sols, react with iron and aluminum compounds, and carry them downward. Thus, soil layers immediately below the mat of forest litter lose organic matter, iron and alumina (sesquioxides), fine claylike materials, alkaline earths (Ca, Mg), sodium, and potassium. The organic matter, iron and aluminum compounds, and fine claylike materials removed from the topsoils are deposited in the subsoils. Hence, podzolization results in a relative increase of silica in topsoils (as compared with parent material) and a relative decrease in subsoils. This deposition of materials in lower soil layers explains the heavy-textured, yellowish-brown or coffee-colored lower layers in many podzols; and in ground-water podzols, massive hardpans (ortstein). Explanations of the gray-brown, red, and yellow colors of forest soils are given in the following chapter.

Attention is called to the fact that podzolization is also effective in local situations in humid regions, in poorly drained and water-saturated sandy deposits. Hence, such soils as ground-water podzols, in which the B horizons may be ortstein, if cemented into massive hardpans, or orterde, if slightly and irregularly cemented.

Laterization. *Laterization,* a soil-forming process in humid and subhumid tropical regions, results in lateritic soils in first stages, and true laterites in last stages.[4] In this soil-forming process, the infiltering and percolating rain water, under the influence of heat, removes silica from the soil mass, which removal results in relative increases in aluminum compounds and iron oxides. Laterites are characterized by aluminum and/or iron hydroxides, with minimum

[3] *Podzol,* a Russian term which means ash (bleached), hence strongly acid, ash-colored soil.

[4] The term "laterite" was coined by Buchanan (Eng.) in 1807, when in India certain soils attracted his attention, particularly those which supplied building material. Laterite, from *later,* meaning brick.

silica and low base-holding capacity. In some places, iron ore has formed. These facts explain the yellowish-brown and reddish-brown colors of lateritic soils and the red-brown color of laterites.

In laterization, the removal of silica from the soil mass is accompanied by the removal of alkaline earths and alkalies to a greater degree than in podzolized soils, until in laterites very small quantities of these elements are retained. The essential character of lateritic soils are (a) almost exclusive mineral composition and (b) in upper layers, accumulations of sesquioxides and low content of silica, alkaline earths, alkalies, and humus.

There is no sharp division between areas of podzolized and laterized soils. Podzolization and laterization overlap. On going from a humid temperate forest region toward the tropics, one will observe, first, only slight effects of laterization in soils predominately podzolized, as in Mississippi, Alabama, and Georgia; and on approaching the tropics, he will observe more and more definite effects, until in lateritic soils the distinguishing characteristics indicate the soil-forming processes to be predominately laterization. Laterites usually have somewhat acid, red-brown clay surface layers underlaid with iron concretions, crusts, or skeletonlike masses. Probably the acidity develops from podzolization following laterization. There are also ground-water laterites, the results of both podzolization and laterization.

Calcification. *Calcification,* a widespread soil-forming process on grassland areas in subhumid and semiarid climates and in arid regions, is so called because it results predominately in the accumulation of calcium carbonate, concentrating at depths that vary with average annual rainfalls, as typically shown in the soils that characterize the well-drained uplands of the broad belts of black, brown, and gray soils one would cross in going from Sioux City, Iowa, to a desert area in northern Wyoming (p. 102). The calcium, together with magnesium, originate in the weathering of the mineral soil-forming materials. Because of the limited rainfalls, there is not sufficient infiltrating and percolating rain water to fully remove these basic elements. Accumulations of organic matter or humus also vary with the annual rainfalls. In contrast with podzolized and laterized soils, soils with free lime carbonate are not acid, which indicates that in these nonacid soils the base-exchange compounds are saturated with bases, especially exchangeable calcium.

In areas between definitely podzolized forest soils, which are acid, and black-earth soils (chernozems), which contain free carbonate

of lime, podzolization and calcification overlap. The division between such areas may be between soils that have predominately podzolized features, on the one hand, and soils that show the predominant action of calcification, on the other. Where forests have encroached upon black-earth areas, notably in Russia, podzolization has resulted in the deterioration of chernozems, hence *degraded chernozems.* In some places, as in the United States, somewhat podzolized, more or less acid soils of well-drained, tall-grass prairie areas lie between strongly podzolized forest soils and areas of chernozems (p. 102).

Salinization and desalinization. Commonly in arid and semiarid regions, poorly drained depressions, seepy areas, old exposed lake beds, and low borders of salt lakes are characterized by saline soils; also, some poorly drained depressions or low areas in humid and subhumid regions, and low alluvial deposits along seacoasts in humid regions. Saline soils contain more than normal quantities of soluble salts, more than about 0.2 percent. The soil-forming process that results in this predominant saline character is called *salinization.* The salts involved in this process include sodium chloride, sodium sulphate, sodium carbonate, sodium bicarbonate, calcium sulphate, calcium chloride, and also in some places, magnesium sulphate and chloride or potassium salts. The origin of these salts may be, directly, the parent soil-forming mineral materials, or, indirectly, brackish lake or sea water. Salinization depends on ground water that contains soluble salts, which water becomes effective through its capillary rise and evaporation, leaving the salts to concentrate and/or accumulate in the soils and on the ground surface. In some places in irrigated areas, the rise of the ground-water table, even with the use of salt-free water, has effected artificial salinization, with harmful results in crop production.

In some places, especially in poorly drained areas in arid and semiarid regions, highly saline soils are classed as *alkali,* which soils contain (a) an excess of soluble "white-alkali" salts (no sodium carbonate), or (b) an abnormal quantity of absorbed sodium, or (c) both an excess of soluble white-alkali salts and an abnormal quantity of absorbed sodium. White-alkali soils are so called because of the presence of surface crusts of white salts, and black-alkali soils are indicated by salt crusts stained dark with organic matter (sodium carbonate dissolves organic matter).

Desalinization is the removal of soluble salts from saline soils usually through leaching with water, naturally or artificially—naturally, on permanent lowering of the water table in the development of soils classed as Solonetz, for example; and artificially, in the reclamation of alkali soils.

Gleization. *Gleization,* a soil-forming process which, acting under standing water and water-saturated conditions, has resulted in the development of glei (blue and gray clay) subsoils, a predominant distinguishing feature of soils of various kinds in all climatic regions, including tundra soils, meadow soils, peat and muck soils, and certain other soils (planosols) of wet level areas originally with grass or forest cover. Many of these soils have dark-brown or black topsoils; with many, the topsoils consist mostly or largely of organic matter.

Under standing water or permanent saturation, hence under anaërobic conditions, iron compounds are reduced to soluble ferrous forms (bluish green, as sulphate; colorless, as chloride), which explains the bluish and gray colors of the glei subsoils. Under alternating saturated and moist conditions, caused by the rise and fall of the ground-water table, hence with some aëration within the clay mass, the iron in some spots has oxidized to ferric forms (red, brown, yellow), which explains bluish- or gray-clay subsoils marked with reddish-brown streaks or with yellowish- and reddish-brown spots (mottled).

Although soils of many kinds in widely scattered locations have in common a predominant feature developed through gleization, some of these soils are more or less acid, thus indicating the overlapping or conjoint action of gleization and podzolization. Whether these soils are acid depends on such factors as the kinds of salts contained in the ground waters, the chemical nature of parent materials, and the chemical nature of the substances contained in run-off that may concentrate on the areas concerned.

Peat formation. In previous paragraphs, references are made to peat and peaty soils. Such soils result from the action of soil-forming forces on cumulose deposits (see p. 100).

Grass v. forest vegetation. In some places, long conflicts, as it were, have occurred or may still be in progress between plant communities (vegetation) of different types. The effects of such conflicts have been recorded in the very soils themselves. In Russia, for example, conflicts have been between forests and bordering

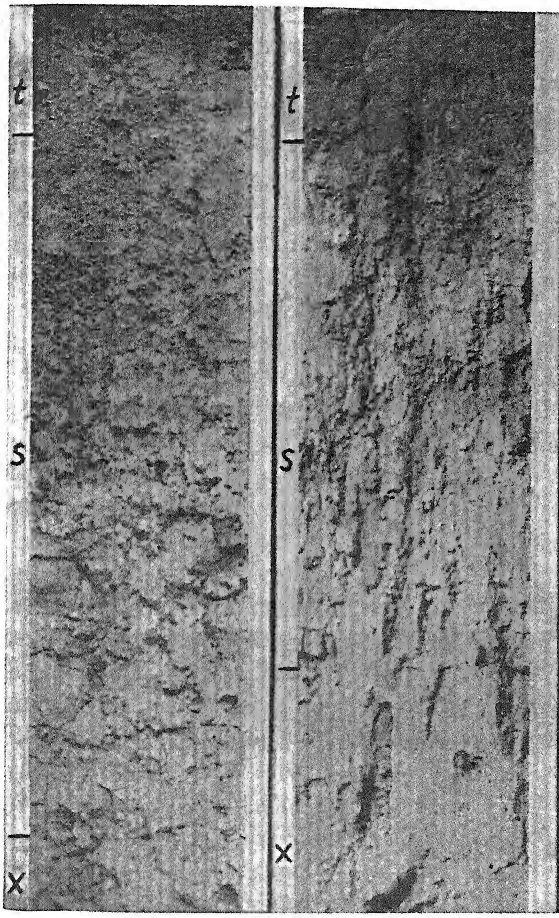
steppes, with consequent degradation of the black-earth soils (chernozems) of the grasslands (Fig. 25). Another example is the conflict that must have been in progress for many centuries between forests and tall prairie grasses for possession of wide expanses of glacial-drift areas in what is now central United States, following the ice age. It is quite evident that the grasses possessed these lands first. Then began the advancement of the forests, which gradually covered wider and wider areas. In some places, however, the grasses, aided by prairie fires and prevailing winds, and protected by streams, must have successfully resisted forest invasion for a long time, as indicated by the dark color, depth, and distinct characteristics of the prairie soils involved. In wooded strips along the east side of some streams and in border zones between what were formerly grassed and forested areas, one may observe definite marks of the success of the forests, as indicated by faint to rather definite podzolization of the prairie soils affected.

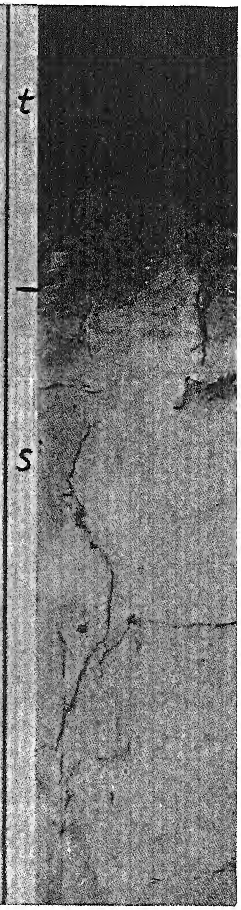
How soils develop. When we consider the principal soil-forming agents—percolating rain water, heat, plants (vegetation), and ground water—it becomes clear that soil development does not start first at the ground surface and then gradually extend downward, even though the contact of some of the soil-forming forces is first made at the ground surface. In the development of a given soil, all the forces involved act throughout the soil mass. However, the degree of action of certain forces or the degree of development of certain soil characteristics may vary inversely with depth, as in the development of acidity (see Fig. 15). On the contrary, some forces act and certain characters develop from below up, as in case of ground water and in the accumulations of carbonate of lime in black-earth and chestnut-brown soils. Further, in a given soil, it is assumed that the topsoil and subsoil have developed together.

Depth of soil. Whether a soil is shallow or deep is determined by (a) depth of the deposit of soil-forming material and (b) depth to which the soil-forming agents have effected development of distinguishing soil characteristics, or effected perceptible changes in the soil mantle, as compared with the original parent material. Soils vary widely in depth. In cool temperate, desert, and semidesert regions, well-drained upland soils are usually a few feet deep, 2½ to 4 feet. In warm humid regions, they are generally deeper than in cool humid regions; and in tropical and subtropical climates, very deep, in some places 100 or more feet deep.

SOIL PROFILES

A vertical section through a soil down to the substratum or parent material is its profile, which may be observed in a fresh roadcut or





I II

Fig. 22. Profiles of two typical upland soils: I, Chestnut; II, Brown soil of semiarid steppes. t, s, x, A, B, C, horizons. (After Filatov, Russ., 1927.)

Fig. 23. Profile of a peaty glei (gley) soil. s, glei subsoil.

excavation 5 or more feet deep. When we consider the nature of the soil-forming forces and their downward-upward actions in deposits of originally loose geologic materials, soil profiles must be of

vertical sections. Commonly, in humid and subhumid regions, the vertical section of a mature soil reveals two clearly defined major layers, topsoil and subsoil, or A horizon and B horizon; whereas in arid and semiarid regions, soils usually do not have definitely defined layers, even if the soils are well developed. Thus the term "soil profile" does not necessarily imply definite horizons. In many a soil, the topsoil or subsoil, or both, may embrace two or more component layers, which are usually designated as A_1, A_2, B_1, and B_2. Immediately beneath subsoils are substrata materials unaltered by soil-forming forces. These substrata are designated in soil science as *C horizons*, which are regarded as representing parent materials.

Eluviation and illuviation. Definitely defined subsoils are commonly heavier textured than the topsoils, which results from the removal of claylike materials and substances in solution from the topsoils, and their deposition in the lower layers. These removal and deposition processes in soil formation are called, respectively, *eluviation* and *illuviation.* The active agent involved is infiltering and percolating precipitation water. Horizons, commonly topsoil layers, that have lost materials through eluviation are described as *eluvial* or *eluviated;* and horizons, commonly subsoil layers, that have received the materials, *illuvial* or *illuviated.*

Soil v. soil profile. A soil as a concrete object is a material thing. We gain knowledge about a soil through its characters or qualities. That's the only way open. Any one of these qualities cannot have materiality. One of the best ways to find out what a soil is like is to study its profile. Obviously, its profile is not the soil itself, but only an attribute, hence nonmaterial. Thus, logically, a soil profile cannot contain stones, for example, any more than brown or gray color can contain stones. Nor can a soil profile have color, reaction, or texture. The soil itself, or its various layers, may contain stones and have color, reaction, and texture. When there is no roadcut or excavation, as in soil-survey work, a convenient way to determine the characteristics of soils, by study of their profiles, is through the use of a soil auger.

Soil description. In describing a soil, one usually states what is revealed in a cross section of it, from surface down. Accompanying the description of the soil itself, there should be a description of the substratum, in order to supply information about the character of the material from which, presumably, that soil has developed.

Solum v. soil. The term "soil" has long been used, and is still commonly used, to designate, in general, that part of the ground

which is directly affected by tillage implements. Frosterus (Fin., 1924) suggested the term "solum" to designate, in a given soil, the whole soil zone above the C horizon, which shows discernible effects of the action of soil-forming forces. Where soil layers are present, *solum* includes topsoil and subsoil. In soil science, the concept *soil* also connotes this very same meaning. However, the word "solum" serves a very useful purpose, in lucid expression of thought, in directing attention clearly to the vertical aspects of a soil from the surface to the C horizon, as, for example, solum distribution of clay and solum reaction.

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REVIEW QUESTIONS

1. Compare the ancient and modern concepts of soils.
2. Describe deposits of soil-forming materials; state origin.
3. Describe the transformation of rocks (granite, for example) into soils. Distinguish between rock weathering and soil formation.
4. Distinguish between factors, agents, and forces of soil formation.
5. Give examples of the predominance of various factors and forces of soil formation or development.
6. What is the basis for differentiating between rock-weathering and soil-formation processes? Illustrate.
7. Name the soil-forming processes that are dominant in the great soil belts of the world, and describe the action of each.
8. Name other soil-forming processes; describe and give examples.
9. Give examples of the overlapping or conjoint action of soil-forming forces. Give reason for such overlapping.
10. Explain how soils may show biotic conflicts.
11. Describe in general how soils form or develop. What depth?
12. Compare the meanings of *solum, soil,* and *profile.*
13. Explain the development of lighter-textured topsoils and heavier-textured subsoils in many soils.
14. Describe a soil of which you have knowledge.

CHAPTER 7

SOIL CLASSIFICATION

Many different soil classifications have been made, based on some particular feature or for some specific purpose to fit current needs,

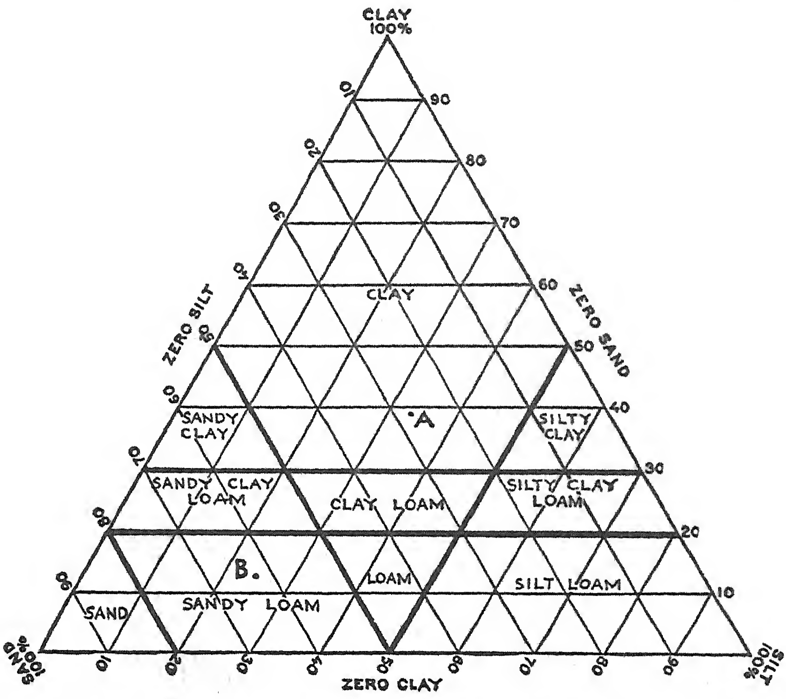

Fig. 24. Triangle showing percentage composition, in terms of sand, silt, and clay, of 10 principal soil classes. Point A represents a clay composed of 28 percent sand, 33 percent silt, and 39 percent clay. Point B represents a sandy loam composed of 63 percent sand, 24 percent silt, and 13 percent clay.

rather than on the natural or scientific basis. Classifications in which attention is laid on the human use of soils are artificial.[1]

[1] WOLF, A. SCIENTIFIC METHOD. Encyclopedia Britannica, Vol. 20, p. 129. 14th edition. 1929.

Scientific classification, on the other hand, has to do primarily with the true *nature* or with all the *distinguishing characteristics* of the soils themselves. Illustrations of artificial soil classifications are given to explain briefly the origin of many of our common descriptive terms.

ARTIFICIAL SOIL CLASSIFICATIONS

An ancient scheme of soil classification, like that devised by Cato about 2,100 years ago (Ch. 1), was based on crop adaptation. Such a classification may serve a useful purpose even in modern times. Other old classifications are *mineral* and *organic* soils.

Textural groups. Probably the most common and widely used classification is that which is based on the texture of soil materials that constitute topsoils, as ascertained by mechanical composition. This classification serves a very useful purpose even in soil science (Fig. 24). The designation of earthy materials according to texture is probably the oldest soil classification, having originated with concepts indicated by such common terms as "sand," "clay," and "loam."

Investigators in the United States Department of Agriculture have defined 20 principal classes of soils based on mechanical composition, as follows:

Classes of Soils Based on Mechanical Composition

1. Soils containing less than 20 percent clay:
   - Soils containing less than 15 percent silt and clay—
     - Sand:
       - Coarse sand (35 percent or more fine gravel and coarse sand, and less than 50 percent fine or very fine sand).
       - Sand (35 percent or more fine gravel, coarse and medium sands, and less than 50 percent fine or very fine sand).
       - Fine sand (50 percent or more fine and very fine sands).
       - Very fine sand (50 percent or more very fine sand).
   - Soils containing from 15 to 20 percent silt and clay—
     - Loamy sand:
       - Loamy coarse sand (35 percent or more fine gravel and coarse sand, and less than 35 percent fine and very fine sand).
       - Loamy sand (35 percent or more fine gravel, coarse, and medium sands, and less than 35 percent fine and very fine sand).
       - Loamy fine sand (35 percent or more fine and very fine sands).
       - Loamy very fine sand (35 percent or more very fine sand).

Soils containing from 20 to 50 percent silt and clay—

Sandy loam:

Coarse sandy loam (45 percent or more fine gravel and coarse sand).

Sandy loam (25 percent or more fine gravel, coarse and medium sands, and less than 35 percent very fine sand).

Fine sandy loam (50 percent or more fine sand, or less than 25 percent fine gravel, coarse and medium sand).

Very fine sandy loam (35 percent or more very fine sand).

Soils containing 50 percent or more silt and clay—

Loam and silt loam:

Loam (less than 20 percent clay, from 30 to 50 percent silt, and from 30 to 50 percent sand).

Silt loam (less than 20 percent clay, 50 percent or more silt, and less than 50 percent sand).

2. Soils containing from 20 to 30 percent clay:

Clay loam:

Sandy clay loam (less than 30 percent silt, and from 50 to 80 percent sand).

Clay loam (from 20 to 50 percent silt, and from 20 to 50 percent sand).

Silty clay loam (from 50 to 80 percent silt, and less than 30 percent sand).

3. Soils containing 30 percent or more clay:

Clay:

Sandy clay (from 30 to 50 percent clay, less than 20 percent silt, and from 50 to 70 percent sand).

Clay (30 percent or more clay, less than 50 percent silt, and less than 50 percent sand).

Silty clay (from 30 to 50 percent clay, from 50 to 70 percent silt, and less than 20 percent sand).

Some special classes of soils have also been defined, as follows:

Peat (65 percent or more organic matter, sometimes mixed with considerable sand, silt, and clay).

Peaty loam (from 20 to 25 percent organic matter mixed with much sand and silt, with but little clay).

Muck (from 25 to 65 percent well-decomposed organic matter, mixed with much clay or silt and some sand).

Gravelly soil (containing 30 or more percent of fine, medium, and coarse gravel or stones ranging up to 2½ inches in diameter).

Stony soil (containing a comparatively large number of stones over 2½ inches in diameter). (See p. 28.)

Classes based on soil consistence. Atterberg (Swed., 1911-1916) has suggested classification of soils according to the physical char-

acteristics of topsoil material, as regards plasticity and firmness. (Ch. 3.)

Classes based on soil-forming materials. It is often convenient to class soils or to describe them in terms that indicate the manner in which the soil-forming materials had accumulated, such as residual, sedimentary, marine, alluvial, lacustrine, glacial, loess, colluvial, and cumulose.

Physiographic classification. Before soils were recognized as natural bodies whose characteristics have developed as the result of specific forces, broad classifications were attempted on the basis of the dominant physical features of a country. For example, the United States was divided physiographically into 7 provinces and 6 regions which together designated 13 major classes into which the soils of the States might be grouped. These physiographic divisions were: (1) glacial-lake and river terraces; (2) glacial and loessial; (3) limestone valleys and uplands; (4) Appalachian Mountains and Plateaus; (5) Piedmont Plateau; (6) river flood plains; (7) Atlantic and Gulf Coastal Plains; (8) Great Plains region; (9) Rocky Mountain region; (10) Great Basin region; (11) southwest arid region; (12) northwest intermountain region; and (13) Pacific coast region. In the physical regional features one can see the probable basis of such a broad grouping of soils, namely, the general character of parent materials.

Rock basis. A logical geological grouping would be to classify soils according to the rocks from which soil-forming materials are derived. Such a scheme may meet certain practical needs of local or restricted areas, but such a classification does not take into consideration the distinguishing features of the soils themselves. Fallou (1882) followed such a scheme in central Germany, and also Hall and Russell (1911) in southeastern England.

Classification on color basis. Another suggestion was the grouping of soils according to their color. In the United States such a classification was proposed, including (1) dark-colored soils (black, very dark brown, dark-colored calcareous, "chestnut-brown," alluvial, marsh, and swamp soils), and (2) light-colored soils (light-brown silt loams from calcareous glacial drift, brown stony loams, gray to brown silty soils, brown silt loams, yellowish soils, and reddish-brown soils). But color is not a permanent characteristic, and just one attribute does not allow scientific grouping, inasmuch as all distinguishing features should be taken into consideration.

SCIENTIFIC CLASSIFICATION OF SOILS

The basis for a natural classification of soils was established by Dokuchaev (U.S.S.R.) in 1879 (p. 95), and later developed by Sibirtsev (1900-1901), Glinka (1909-1914), and other Russians, by Ramann (Ger., 1917), and by Marbut after the publication of Glinka's book, *Die Typen der Bodenbildung, ihre Klassifikation und geographische Verbreitung,* in 1914. Distinguishing characteristics of soils developed in consequence of soil-forming forces constitute the basis of scientific classification of soils. This is the only generally accepted scientific basis. In fact, there is no other.

In developing natural classification of soils, two procedures may be followed, one of division and the other of addition; each, however, supplements the other. In the first procedure, land divisions are made on the basis of dominant soil characteristics. Each such zone represents a soil class, inasmuch as the upland soils embraced have in common one or more distinguishing feature. For example, the United States may be divided, roughly by a line running from the northwestern part of Montana to middle Texas, into two almost equal parts, so far as soils are concerned (Fig. 21). The eastern part embraces predominately acid or podzolized soils, whereas the western part embraces predominately nonacid soils.

The eastern part of the United States may be subdivided into five principal areas: four zones of gray, brown, gray-brown, and yellow and red soils (all forest soils), and a zone of prairie soils developed on prairie grasslands (Fig. 21). The western half of the United States includes four principal zones, as determined by kinds of soils: a belt of black-earth soils (chernozems), two parallel belts of chestnut-colored and brown plains soils, and deserts (Fig. 21). Subdivisions of each zone may be made, finally down to a great many comparatively small land areas each of which embraces a group of soils that are similar in many respects (soil-type group).

In such divisions, one should not err by dividing "the soil, an organized body" first into halves, then fourths, and finally into many fractional appendages, then regard the "integral parts" as "definite entities," the units used in soil classification.

Soils by zones. We return to land areas or zones that represent various kinds of soils. The question arises whether the concept *zonal* can have a place in a scientific soil classification—that is, whether *zonal* can be an inclusive soil class, inasmuch as this term

immediately brings to mind the idea of certain land areas or a physiographic concept. Here one should keep in mind the basic fact that *all classes in a true scientific soil classification must be based on distinguishing soil characteristics developed as the result of the action of soil-forming forces.* Accordingly, *zonal* may name an inclusive class, or a large division, in a scheme of soil classification only when it connotes those well-defined soil characteristics that reflect, over a given climate-vegetation zone, predominant influences of the climatic and biotic forces, for such features establish relationship between the upland soils of that zone. Taking into consideration the fact that all the countries of the world may be divided into climate-vegetation zones, we may draw the inference that most all the upland areas of the earth represent Zonal soils, or principal great soil groups.

ZONAL SOILS

As regards the principal great soil groups, two things should be kept clearly in mind: (1) Each group represents upland soils whose distinguishing features reflect predominately the influences of climatic and biotic soil-forming forces, and (2) the class name of each group implies these distinguishing characteristics.

The principal great soil groups are listed on two pages herein, together with related information regarding region or area where the soils occur, climate, annual rainfall, native vegetation, and some main characteristics. Notes regarding the soils represented by these principal great soil groups follow.

Tundra. The term "tundra," from Russian meaning treeless plain, is used to designate the soils of this frigid zone, hence the Tundra group. During the brief summer, these soils in extensive areas, even under limited rainfall, become wet like quaking bog. Their subsoils usually remain frozen the year round. Here dense growths of mosses and lichens, with herbs and dwarf shrubs, tend to form peat. There are also so-called dry-tundra soils. A typical Tundra soil has been described as follows: A peaty cover, then a thin humus layer underlaid by a yellowish-brown mineral layer about 2½ inches thick, and, in turn, by gray, sticky clay to a depth of about 6 inches. Immediately below the gray layer is another one of yellowish-brown material, below which is a compact brownish-gray subsoil. The substratum is brownish gray. The gray clay and ground conditions indicate gleization.

Principal Great Soil Groups

(Based on typical virgin soils of well-drained uplands)

Class	Occurrence or Location	Rainfall (av. ann.)	Native Vegetation	Soil Characteristics: Topsoil	Soil Characteristics: Subsoil
Tundra	Frigid (arctic) region	Less than 20 to more than 30 inches	Mosses and lichens with herbs and shrubs	Shallow, peaty More or less acid	Grayish, mottled Frozen year long Somewhat acid
Podzol	Forest and heath lands in temperate to cool humid regions; also under forests on mountains	25 to 50 or more inches	Conifers; mixed conifers and deciduous trees; deciduous forests; also heath	A_1 thin, dark colored A_2 ash gray Strongly acid	B_1 yellowish brown to dark brown B_2 yellowish brown Strongly acid
Brown Podzolic	Forest lands in cool-temperate, humid areas	30 to 50 inches	Deciduous forests; mixed conifers and broad-leaved trees; conifers	A_1 thin, dark gray A_2 thin, grayish brown or yellowish brown Acid	Yellowish or grayish brown, heavier textured Acid
Gray-Brown Podzolic	Forest lands in temperate, humid areas	25 to 80 inches High fall mostly in winter	Mostly deciduous forest trees; also conifers, as on mountains	A_1 thin, dark colored A_2 grayish brown Acid	Yellowish or reddish brown, illuviated Acid
Red Podzolic	Forest lands in warm-temperate, humid areas	25 to 50 inches	Deciduous forest trees with some conifers	A_1 thin, dark colored A_2 yellowish brown, leached Acid	Deep red, illuviated Acid
Yellow Podzolic	Forest lands in warm-temperate, humid areas	25 to 50 inches	Coniferous forests; also mixed conifers and deciduous trees	A_1 thin, dark colored A_2 grayish yellow, leached Acid	Yellow, illuviated Acid
Prairie	Prairies and high-mountain bunchgrass areas of cool humid areas	25 to 40 inches	Prairie grassland, also tall bunchgrasses	Dark brown or grayish brown Slightly to rather strongly acid	Lighter brown Slightly to moderately acid
Reddish Prairie	Prairies of warm-temperate, humid regions	28 to 35 inches Summers hot and rather dry	Prairie grassland, also mixed tall and short grasses	Dark reddish brown Acid	Reddish brown, somewhat illuviated Moderately acid
Reddish-Brown Lateritic	Wet-dry tropical regions	Moderately high	Rain forests (selvas) to edge of savannas *	Reddish brown, granular, clayey More or less acid	Deep red, friable, granular clay More or less acid
Yellowish-Brown Lateritic	Wet-dry tropical regions (subhumid to humid)	Moderate to high	Evergreen and deciduous broad-leaved trees	Yellowish brown More or less acid	Yellowish brown More or less acid

Laterite	Moist, wet-dry, tropical regions	High to moderate	Grasses (savannas), also selvas (rain forests)	A_1 thin, dark colored A_2 red-brown, leached Somewhat acid	Deep red Slightly or weakly acid
Chernozem	Grasslands,† or plains, in temperate to cool, subhumid regions	18 to 30 inches, with summer rainfall	Mixed tall and short grasses, also tall bunchgrasses	Deep, black or very dark brown Not acid nor calcareous	Brown or lighter colored Carbonates 20 to 40 inches from surface
Degraded Chernozem	Forests encroaching on grasslands in temperate to cool, subhumid to humid regions	20 to 30 or more inches	Forest trees and grasses	A_1 dark brown to black A_2 grayish Slightly acid	Brown to gray veined Still some carbonates in deep subsoil
Chestnut	Short-grass plains areas in cool-temperate subhumid areas	14 to 20 inches	Plains grassland, also short grasses, and also bunchgrasses with brush	Dark brown, friable Slightly to distinctly calcareous	Brown or grayish brown Calcareous to limy
Reddish Chestnut	Short-grass plains areas in warm-temperate subhumid areas	15 to 30 inches	Bunchgrasses with shrubs; short grasses; mixed grasses with brush or dwarf trees	Dark reddish brown Neutral to alkaline, not calcareous	Reddish brown Lime accumulations
Brown	Plains and intermountain areas in temperate or cool semiarid areas	10 to 20 inches Summers dry and rather hot	Plains grassland, also bunchgrasses with shrubs, also short grasses	Brown or light brown Alkaline-calcareous	Lighter colored, caliche common Calcareous, limy
Reddish Brown	Plains grasslands and grass-shrub areas in warm-temperate semiarid areas	10 to 20 inches Long, hot, dry summers	Short grasses, also tall and medium bunchgrasses with semidesert shrubs	Reddish brown Alkaline-calcareous	Heavier, reddish brown or grayish brown, caliche in places Limy
Desert (Sierozem)	Warm to cool-temperate arid regions	3 to 10 inches	Desert shrubs with annuals (herbs)	Light grayish Alkaline-calcareous	Light grayish, hardpan (caliche) common Calcareous
Red Desert	Hot arid regions	3 to 10 inches	Desert shrubs with annuals (herbs)	Light reddish brown Alkaline-calcareous	Reddish brown, friable Highly calcareous, caliche common
Shantung Brown or Noncalcic Brown	Mountains, intermountain valleys, hills, and plateaus in wet-dry subhumid areas	15 to 25 inches Cool winters, rather hot, dry summers	Chaparral ‡ (brush) with bunchgrasses and some short trees, also woodlands §	Brown or reddish brown Slightly acid to neutral	Lighter brown to dull reddish brown Neutral or slightly alkaline Noncalcic

* Savanna; vegetation consisting of grasses and scattered short trees, or land area thus covered.

† Grassland; vegetation consisting of grasses and allied plants, or land thus covered.

‡ Chaparral; vegetation which occurs below woodlands and above semidesert zones, and which consists of evergreen oaks or other stiff or thorny brush or dwarf trees.

§ Woodland; vegetation which occurs immediately below saw timber (forest) areas, and which consists of junipers, piñons, scrub oaks, and/or other short trees growing in open orchard-like stands on grassy and herb-covered mesas, ridges, and slopes; land with such vegetation.

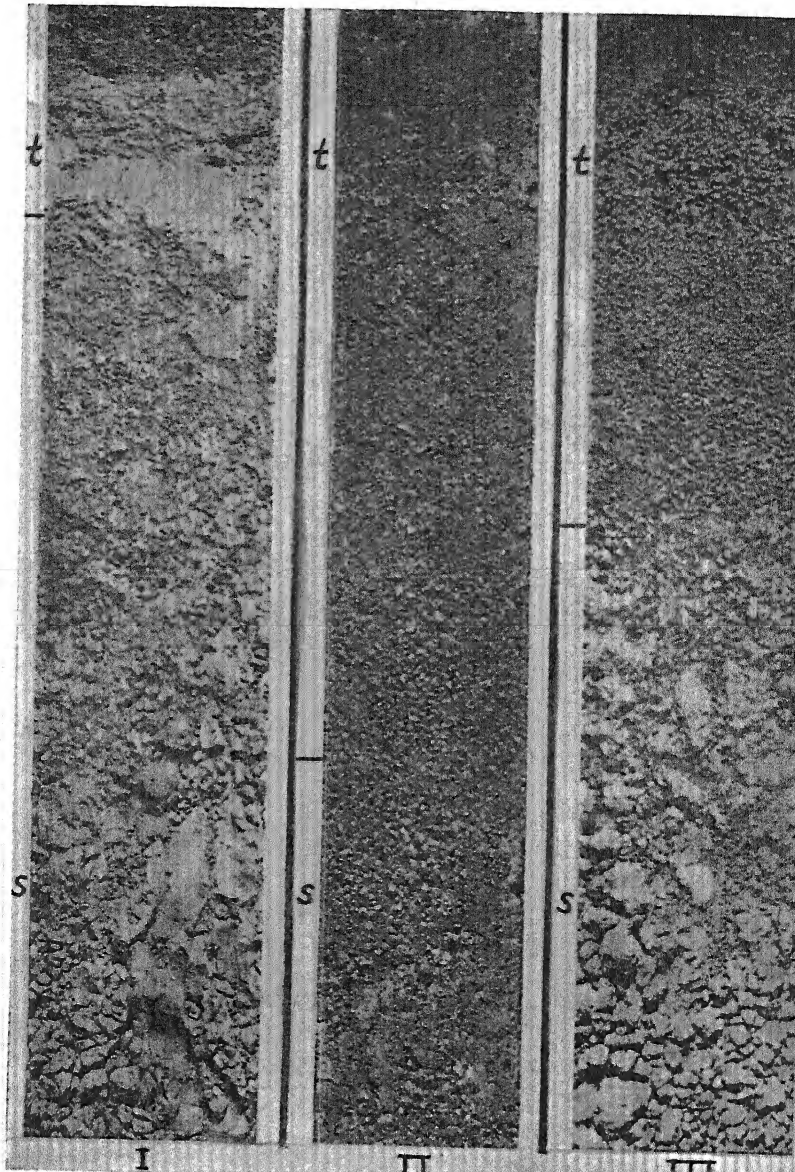

Fig. 25. Profiles of three typical soils: I, a strongly podzolized soil; II, a deep black-earth soil (Chernozem); III, a degraded chernozem. t, Topsoil, or A horizon. s, Subsoil, or B horizon. (After Filatov, Russ., 1927.)

Podzol. Podzol, as a great soil group, represents soils with gray, bleached, strongly leached topsoil layers, developed under forests and heath covers. The latter vegetation consists of ericaceous plants (acid-soil shrubs) which may characterize waste lands, as in Great Britain. The subsoils, or B horizons, are colored yellowish brown to dark brown, and are illuviated, including depositions of iron oxide, aluminum compounds, and in some, organic matter. Topsoils and subsoils of podzols are strongly acid (p. 110). Soils of this class occur in various countries of the world. They also occur on forested areas of mountains, even those of arid-semiarid regions, as in southwestern United States.

Typical podzols may be described as follows:

Ground mats of organic matter (mull or trockentorf) which consist of leaves, mosses, and other forest litter. Designated as "A_0."

Topsoils, or A horizons, composed of two layers: A_1, a 1- or 2-inch layer colored dark with humus; A_2, an 8- or 10-inch ash-gray layer, with relative increase of silica due to removal of clay.

Subsoils, or B horizons, to ground depths of about 30 inches, consist of materials heavier textured than those of the A horizons. B_1 is coffee-colored, and B_2 is yellowish brown, the darker color grading into the lighter below.

Substrata, or C horizons, are colored brownish yellow.

Podzols have gray topsoils and dark-colored subsoils for two principal reasons: (1) Acid colloidal organic matter in suspension does not accumulate in the podzolized A horizons but descends to lower layers. (2) The iron compounds in the topsoils are dissolved and leached out, owing to the fact that, as temperature conditions do not favor oxidation of the iron to ferric forms, ferrous iron reacts readily with, and is carried down by, the humic acid solutions.

A description of the dissolving processes and precipitation of iron, organic matter, and aluminum in some typical podzols is given: In all cases the dissolving solutions contain humic acids (organic sols). The principal iron sol concerned, according to Anderson and Byers (1933), is ferrous hydroxide which has marked basic properties and which probably forms, under cool conditions, during the hydrolysis of mineral soil particles that contain ferrous iron. Precipitation of the sesquioxides and organic matter in the subsoils may result from neutralization of the opposite charges that stabilize the separate sols (Ch. 4).

The solutions from the coverings of very acid organic matter,

which contain acid organic sols, react readily with ferrous hydroxide as they descend, forming complex and rather stable ferrous humate which is carried down either in solution or as highly dispersed colloidal material. The ferrous humate is affected more or less by oxidation as it descends; and when it reaches less acid mediums, it is precipitated, hydrolyzed, and oxidized, and forms ferric hydrate and humus. The organic part of the ferrous humate material may be precipitated in a rather narrow zone, and the iron in a somewhat wider zone, in the upper part of the B horizons. In some of these soils, some of the organic matter escapes the precipitating effects of oxidation, filtration, and less acid mediums, and is distributed at greater depths. The same holds true for some of the iron.

The descending solutions of humic acids (organic sols) react also with aluminum hydroxide sols, which suggests the formation of aluminum trihumate. Inasmuch as the aluminum part of this humate is not affected by oxidation, but is affected by filtration and less acid mediums, it is precipitated in a much wider zone than is the iron.

Brown Podzolic soils. The class name "Brown Podzolic" is applied to imperfectly developed upland forest podzols like those in the New England States (Fig. 21). Usually they are stony sandy soils and sandy loams. Typical virgin members of this group, under thin mats of acid organic matter, have thin dark-gray layers (A_1) underlaid by thin grayish-brown or yellowish-brown layers (A_2). Their subsoils, usually to ground depths of about 24 inches, consist of yellowish-brown materials, heavier textured than the topsoils.

Gray-Brown Podzolic soils. Gray-Brown Podzolic soils occur in extensive areas, formerly forested, in eastern United States and in the western part. The textural range of these important soils is wide, from loamy sand to clay loam. Typical virgin members of this group are described in the accompanying table. These soils are similar to the brown soils (brown earth) of Europe, where they have developed under beech forests and to a lesser extent under oak forests.

The color of Gray-Brown Podzolic soils may be explained as follows: The iron of the soils is changed to a reddish-brown ferric oxide which is affected very slightly, if at all, by the weaker solutions of humic acids (organic sols) that descend from less acidic and less thick coverings of organic matter than those of the gray

forest soils. The formation of ferric oxide instead of the ferrous form results not only from more heat but also from the action of the greater heat through longer seasons, as compared with the gray soils to the north. The less stable organic sols that descend from the surface coverings of organic matter are gradually absorbed by the soil materials in the form of very slightly soluble humus, which dulls the reddish color of the iron oxide. This results in a diminishing solum distribution of nitrogen and organic matter. Kind of leaves or species of trees, less accumulation of acidic organic matter as soil coverings (owing to increased decomposition), higher temperature, and more time for soil-forming forces to act are important factors in the development of Gray-Brown Podzolic soils.

Red Podzolic and Yellow Podzolic soils. Soils of the Red Podzolic and Yellow Podzolic groups occur in extensive areas in southeastern and western United States and elsewhere, as in Puerto Rico. Red soils are dominant on much of the Piedmont, and they also occur on the Blue Ridge, parts of the Appalachian Plateau, in the great limestone valley of the Tennessee River, in the Ozark region, and in large areas in California and western Oregon. The yellow soils, for the most part, constitute the sandy lands of the Coastal Plain. Owing to accelerated erosion, the soils of the Piedmont are incomplete, hence over extensive areas red subsoils are exposed.

With the exception of red soils like those of the *Penn* series, of the Gray-Brown Podzolic group (red color of geologic origin), brown, red, and yellow soil colors represent successive stages of oxidation and hydration of the iron in soils. Through more oxidation effected by more heat acting through longer seasons (as compared with the forest soils to the north), the iron is changed to red, unhydrated, ferric oxide (Fe_2O_3), as red hematite, which gives soils a deep-red color. Diminishing quantities of organic matter tend to brighten their appearances; and through podzolization, red color fades, hence variation in colors.

Inasmuch as the red and yellow soils have developed on areas that have similar forest vegetation, the vegetation itself cannot account for the yellow color. The explanation is to be found within the soils themselves. In soils whose topsoil materials, particularly, are open or sandy, the heat penetrates deeper and causes hydration of the red iron oxide, thus ultimately forming yellow hydrated iron oxide ($2Fe_2O_3 \cdot 3H_2O$), such as limonite, giving the soils a yellow color. The heavier-textured soils of the southeastern States, such as

those of the Piedmont, are red, owing to erosion and slower oxidation, although where normally developed, their loamy or sandy topsoils are yellowish or reddish yellow.

Prairie and Reddish Prairie soils. The class names "Prairie" and "Reddish Prairie," as applied to soils, should not be confused with certain other concepts, to wit: *Prairie* originally meant extensive level or rolling grasslands without trees and with deep fertile soils. This word also means a type of vegetation, consisting mainly of tall grasses, as bluestems, needlegrasses, wheatgrasses, dropseeds, Indian grass, poas, and, in poorly drained areas, sedges. Some parts of the extensive prairies of the Mississippi Valley, for example, consist of well-drained level and rolling lands of dark-brown and grayish-brown soils (northern) and reddish-brown soils (southern); whereas other areas consist of flat lands with restricted drainage, as in southern Illinois. Although most of the soils of these prairie areas have developed under tall prairie grasses, *in soil classification only the dark-brown and grayish-brown soils of naturally well-drained prairie uplands are represented by the Prairie group,* and the reddish soils, by the Reddish Prairie group. The soils represented by these two broad groups reflect predominantly the influences of climatic and biotic soil-forming forces. The soils of the poorly drained prairie lands, on the other hand, are classed as Planosol; the distinguishing characteristics common to all members of this class reflect the predominant influence of a local factor, namely, ground water.

Attention is called to the somewhat lighter color of the Prairie soils in the Pacific coast area and in some areas in Idaho, as compared with those of Iowa and southern Minnesota, for example, probably the influence of a warmer climate and low-summer and high-winter distribution of rainfall (p. 105).

Soils represented by the Prairie and Reddish Prairie classes are more or less podzolized, as indicated by the grayish coating of the structure particles and by acidity (Fig. 15, *Carrington silt loam*).

Lateritic soils and laterites. On the basis of soil characteristics that reflect predominantly the action of laterization, effected by climatic and biotic forces, three great soil groups are listed, namely, Reddish-Brown Lateritic, Yellowish-Brown Lateritic, and Laterite (see also pp. 102, 110, and 111).

Chernozem and Degraded Chernozem soils. Of the black-earth soils, or chernozems, two great groups are recognized,

Chernozem [2] and Degraded Chernozem. In the United States, chernozems occur in the central and north-central parts, also in the Palouse country of southeastern Washington and northeastern Oregon. Chernozems occur in areas in which the larger part of the annual rainfall occurs during summer months. Russia has an extensive area of degraded chernozems.

Chestnut and Reddish Chestnut soils. Like most of the chernozems, the soils represented by the Chestnut and Reddish Chestnut groups characterize plains grasslands. In the United States, for example, they occur wholly within the short-grass plains (Great Plains), between chernozems to the east and brown semidesert soils to the west. As the climate gradually changes from subhumid to semiarid, the soils become lighter in color, organic matter diminishes (because of less natural vegetation), and crumb structure in topsoils finally disappears. The Reddish Chestnut soils, because of warmer climate, contain less organic matter than those represented by the Chestnut group, hence are somewhat lighter in color. The soil zones of lime accumulation are firmer; in some situations, gypsum has accumulated. Also, there is increased oxidation of the iron, hence the reddish color. (See also pp. 102 and 105.)

Brown and Reddish Brown soils. Soils with distinguishing features implied in the class names "Brown" and "Reddish Brown" characterize semidesert grasslands. In the United States, for example, they occur in belts that border deserts in places on the west and belts of Chestnut and Reddish Chestnut soils on the east. The lighter colors of these semidesert soils, as compared with Chestnut and Reddish Chestnut soils, may be explained by the fact that they have developed under less grass. (See also p. 105.)

Desert and Red Desert soils. Soils of upland desert areas range in color from grayish to reddish, hence two broad groups, Desert (Sierozem) [3] and Red Desert, which groups represent soils that characterize, respectively, warm to cool-temperate arid areas and warm temperate and tropical deserts. The friable, granular character of desert upland soils indicate predominant effects of physical processes. And their colors indicate little organic matter, the result of scanty vegetation of the desert-shrub type, with cacti of various kinds. With comparatively little ground protection, the wide difference in day and night temperatures (50° F. or more) is a potent

2 Chernozem (cher'no-zem), from Russian meaning black earth; sometimes spelled Tschernosem.

3 Sierozem, from Russian, meaning gray earth. Probably a separate group.

factor in rock weathering and soil formation—in soil formation, it is probably effective in the development of considerable clay, inasmuch as low drops in day-night temperatures in calcareous mediums cause the condensation of moisture, especially on desert-pavement areas. Also, in some soils the clay content is greater than might be expected to result from the limited rainfall.

Generally, desert soils derived from volcanic materials may contain more clay than those derived from granitic materials. In

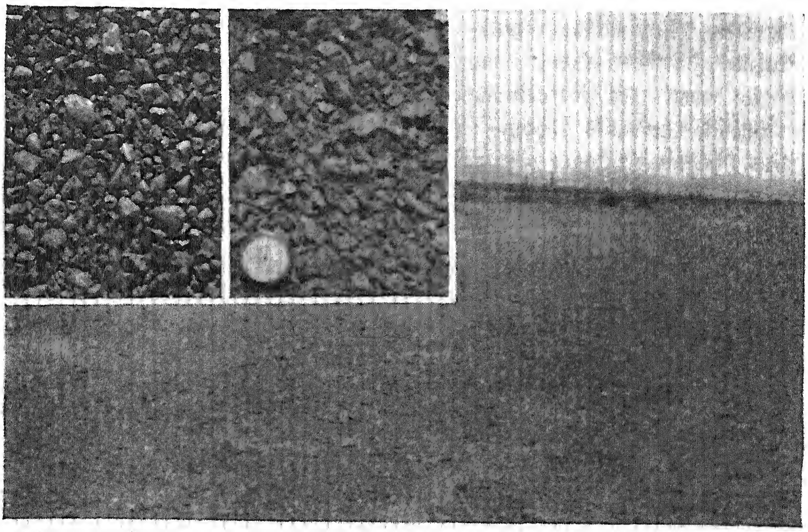

Fig. 26. Desert pavement, lower Gila basin, Arizona. The rock fragments are imbedded in fine material. *Insets:* Pavements from volcanic rock (left) and from schistose rock (right).

either case, when rock surfaces are exposed to differential expansion and contraction, caused by day-night temperature changes and by summer showers on highly heated rocks, it is believed to result in chipping or breaking (spalling) and granular disintegration of the rocks, the results of which are particularly noticeable in gray patches and strips composed of rock grains on low rocky granitic mountains. Hence, desert soils derived from granitic materials, especially near the foot of granitic mountains, contain large quantities of small, angular rock fragments (grains of rock-forming minerals), hence their granular nature or texture.

Striking features of arid lands are desert pavements, which are local areas covered with small, more or less angular, flattish, closely arranged rock fragments, resembling mosaic (Fig. 26). In some

places, the rock fragments are of volcanic origin, in other places, they originated from schistose rocks. Such areas are usually bare of vegetation, except a few scattered shrubs and herbs; and the topsoils contain considerable clay. Another interesting feature of desert lands, in spots and small areas, may be described as efflorescences of snow-white salts of sulphates and chlorides which cover a loose, soft, friable, puffed-up surface layer.

Shantung Brown or Noncalcic Brown Soils. Soils represented by the Noncalcic Brown group are also called Shantung Brown, because they were first observed in Shantung province, northeast China. In the United States, soils of this class occur in the mountains, intermountain valleys, hills, and plateaus of central and southern California, southern Arizona, and southern New Mexico (Fig. 21). For further information regarding these soils, see page 125.

INTRAZONAL SOILS

Other great soil groups, of lesser importance, are based on soil features that reflect predominately the influences of factors other than climate and vegetation. The soils represented by these groups are *intrazonal*, which term implies that they occur within the climate-vegetation soil zones. But in soil science, this name of a class that embraces many lesser great soil groups implies certain well-defined soil features that reflect the influences of local factors like ground water, parent material, and relief, and which features establish broad-class relationships between the soils of certain areas within the great soil belts. Soils of the intrazonal class are represented by the lesser great soil groups listed below.

Wiesenboden (Meadow) soils. Formed in places of restricted drainage under grasses and sedges, mostly in humid and subhumid areas, through gleization with or without some calcification. Topsoils, dark brown or black; and subsoils, mottled grayish materials.

Alpine Meadow soils. Occur in wet mountain meadows near or above the timber line. Formed under grasses, sedges, and flowering herbs, through the same processes as in wiesenbodens. Dark-brown topsoils and grayish subsoils are streaked or mottled.

Planosol. Soils represented by the Planosol group characterize flat, poorly drained, upland areas developed under grass or forest cover in temperate (as in southern Illinois) to tropical humid and subhumid areas. Soil-forming processes involved are podzolization, gleization, also laterization. Topsoils are strongly leached,

grayish brown or brown; subsoils strongly illuviated (commonly with hardpan or claypan). (See Index.)

Rendzina soils. Immature soils developed from chalky or marly materials or soft limestones, under grass or forest cover in humid and semiarid regions, as in the black prairies (black belt) of Alabama and Mississippi (Fig. 21). Topsoils are dark grayish brown to black; subsoils, grayish or yellowish, calcareous.

Brown Forest (Braunerde) soils. Formed from materials rich in bases, under deciduous forests, temperate humid regions, slightly acid.

Ground-Water Podzol. Because of the conditions under which they form, ground-water podzols are widely distributed (pp. 107, 110).

Ground-Water Laterite. Ground-water laterites are restricted to tropical forests; podzolization and laterization (pp. 107, 111).

Bog and Half Bog soils. Implied soil characteristics and predominant soil-forming processes (gleization and peat formation) indicate wide distribution of Bog and Half Bog soils. The soils represented by both groups have developed in swamps and marshy areas and have peaty or mucky topsoils. The subsoils of Bog soils consist of brown peaty materials, whereas those of Half Bog soils consist of grayish mottled mineral materials.

Solonchak, Solonetz, and Soloth soils. The broad-class names Solonchak, Solonetz, and Soloth are of Russian origin, referring to salt; hence the soils represented by these great groups are associated with high salt concentrations, and they occur mostly in arid and semiarid regions. Solonchaks—soils of highest salt concentration—are alkali soils. Sodium solonchaks are of the black-alkali class, also the Szik soils of Hungary and "slick spots" in humid and subhumid regions (p. 112). On leaching by irrigation or permanent lowering of the water table, sodium solonchaks, through desalinization and alkalization, become alkali hardpan soils—solonetz, which have hard, dark subsoils of columnar structure (Fig. 8). Continued leaching of Solonetz soils results in the development of solodi, characterized by thin, friable, grayish-brown A_1 layers, gray leached A_2 layers, and heavy brown B horizons.

AZONAL SOILS

A third division of the great soil groups concern very young and skeletal soils, *which have no well-defined features,* designated as

Azonal. Undeveloped characteristics or beginning of development indicates incipient stages of soil formation. As regards such soils, it is clear that their poorly defined or undeveloped characteristics are regarded valid for establishing broad-class relationships between the soils represented by the various groups of the Azonal class. Of these last broad groups, three are listed below.

Alluvial soils. As the name implies, the Alluvial class represents recently deposited materials on which the soil-forming forces have acted for only a comparatively short time. Alluvial soils are widely distributed throughout the world.

Sand. Like the soils represented by the Alluvial group, loose, dry sands, commonly wind blown, have wide occurrence.

Lithosol. *Lith,* from Greek, means stone; hence lithosols are skeletal soils, which are more or less weathered materials and rock fragments. There are stony parent materials and, commonly, stony ground surface, as on steep slopes and in rough, rocky, mountain areas.

SOILS IN MOUNTAINOUS REGIONS

In a mountainous country, temperature decreases and, generally, average annual rainfall increases with increase in altitude. In a mountainous arid-semiarid region, from low country to high mountain tops, there are four rather uniform or more or less irregular climatic-vegetation zones, namely, arid, semiarid, subhumid, and humid, with corresponding soil zones. Where there is a summer type of annual rainfall (p. 106), the sequence of the soil zones down the slope of a high mountain may be similar to a north-south transection in Russia (p. 102). In southwestern United States, where the annual rainfall is not of the summer type, chernozems may be absent and Shantung Brown soils may occur. Here, as in upper Gila River basin, the sequence of the soil zones from low country to the tops of the higher mountains may be as follows: Red Desert, Reddish Brown, chestnut-colored soils, Shantung Brown, Prairie, and podzolic soils.

SOIL AND LAND SURVEYS

In a reconnaissance, as of a large drainage basin, it may be convenient, especially in a mountainous, arid-semiarid region, to make land divisions based on great soil groups, such as those which represent soils that reflect climate-vegetation influences. On the other hand, in a detailed soil survey—usually of lesser extent, as of

counties or special areas—the smallest land divisions embrace soils that are similar in many respects. According to procedures adopted in the United States, for example, soil-type areas are determined and given soil-type names like *Chester loam*, *Gila sandy loam*, and *Cecil clay loam*, each area embracing a number of closely associated soils that are similar in many respects.

Great soil groups and vegetation relationships. Inasmuch as the types of vegetation that characterize the principal soil belts of the world are determined by climate, in a wild, rough, drainage basin in a mountainous arid-semiarid region, for example, it is possible, on knowing where the various types of vegetation occur, to map not only the rainfall belts but also the kinds of soils by great soil groups. To illustrate, in western United States: Where desert shrubs constitute the native vegetation, those areas have arid climates and there occur Desert or Red Desert soils (whether northern or southern deserts); semidesert grasslands, also semidesert shrubs with bunchgrasses, indicate semiarid climate and Brown or Reddish Brown soils; immediately above the semidesert zone, bunchgrasses with brush or shrubs, or plains grasslands, or grasses with brush or short trees may indicate lower subhumid zones and chestnut-colored soils; higher up, chaparral (brush), also juniper, piñon, or oak woodlands, may indicate upper subhumid zones and chernozems or Shantung Brown soils (depending on type of annual rainfall); higher still, tall-bunchgrass prairies indicate humid climate and Prairie soils; and coniferous forests indicate cool, humid climate and podzolic soils (including podzols). (See pp. 124 and 125.)

Soil-type areas and series. Although in soil surveys as conducted in the United States, for example, a land area that represents a soil type embraces a group of closely associated similar soils, the concept *type* may apply to any representative member of any soil class. As regards soil series, the next larger soil groups embrace various type groups; for example, the *Dunkirk* series includes *D. sand, D. fine sand, D. sandy loam, D. fine sandy loam, D. loam, D. silt loam, D. clay loam*, and *D. clay*. In such a series, the texture of the soils represented by the type classes differ, but certain identical features are implied in the geographic names used as part of the names of soil series, as *Dunkirk, Miami, Cecil*, and *Norfolk*.

Land classification. For practical purposes, a region, county, or watershed may be divided into land-type areas, based on land characteristics, such as physical character of the soils, topographic relief,

and surface and subsurface features or conditions. Other land classifications may be made based on *present land use, land-use capability, recommended land use,* or *program effectuation.* In such land classifications, all of which are artificial, scientific soil classification (soil survey) may aid.

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REVIEW QUESTIONS

1. Explain the difference between artificial and scientific classifications of soils; between soil and land classification. Illustrate.
2. How is scientific soil classification developed? Explain.
3. Discuss *zonal* as applied to soils.
4. Name three divisions of the great soil groups. Give the basis for each division. Name classes in each division.
5. What are the distinguishing features of the soils represented by each of the great soil groups?
6. Explain the various colors of the soils represented by the great soil groups.
7. Describe some features of desert soils; soils of mountainous areas.
8. How can one roughly map the soils of a large area without seeing it?
9. Explain differences in writing the names Podzol, podzols, a podzol, Chernozem, chernozems, prairie soils, Prairie soils, *Chester loam,* Chester loams, a Cecil clay loam, *Chester,* and *Cecil.*

CHAPTER 8

NATURAL ORDER IN SOILS

The second procedure followed in developing scientific soil classification, briefly mentioned in the previous chapter, involves addition, or a building-up process, in which we begin with the individual soils themselves, first grouping them according to similarity in many respects, then building other classes in a scheme of classification. Such a procedure implies natural order in soils—that is to say, soils have in common naturally acquired characteristics some of which run through all the classes formed, hence *natural soil classification*. Natural order in soils is determined by the law of soil genesis, which law may be formulated as follows: *The same natural forces, acting under like circumstances upon deposits of loose geologic materials, produce identical soil characteristics.* Obviously, any class formed in a sound natural classification must agree with the soils represented; also, the broad classes formed must agree with the great soil groups determined by the land-division procedure (Ch. 7).

Nature of soil classification. Classifying earthy bodies as "soil" is a simple process and an everyday occurrence; but in building a scientific classification of soils, the real task consists in showing natural order by first grouping individual soils on the basis of similarity into type groups (as *Cecil sandy loam* and *Chester loam*) and then in grouping the type classes into larger groups, and these groups, in turn, into still more inclusive classes, and so on, until all are collected under one class called "soil." The more inclusive or larger the classes formed, the less the number of soil features that are taken into consideration. In the classification scheme, the successively larger classes are arranged according to *categories*. The scheme takes the form of a triangle or pyramid of which the base represents all the type groups and the apex, the universal group that includes all classes (Fig. 27).

A clear understanding of natural order in soils and of the law of soil genesis which determines this order depends on a knowledge

of the principles of scientific classification and of the general concepts that we deal with in building such a classification.

Principles of classification. The two fundamentals of scientific classification are principles or laws of thought; these are: the *principle of similarity* and the *law of identity.*

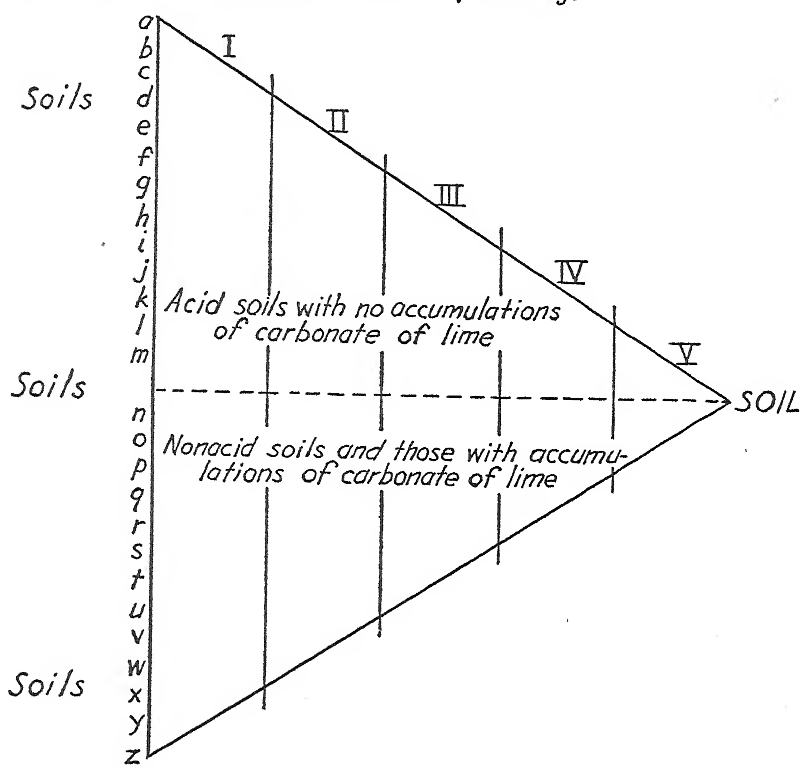

Fig. 27. The structure of a scheme of scientific soil classification, on the sense plane, showing various categories (I, II, III, IV, V) and two great divisions which determine the two major classes of category V. The letters "a" to "z" stand for all soils in the world. The pyramidal shape indicates successively larger and larger classes, but less in number, brought together under the universal concept *soil.* All classes formed represent general concepts.

The principle of similarity in soil classification is applied to the grouping of individual soils according to their close likeness, that is, *resembling each other in many respects.* The application of this principle in soil classification may be described as follows: We may examine a soil that constitutes an area of well-drained upland, having a topsoil of sandy-loam material. This soil has well-

defined features, as shown by its profile. Some distance away we may find another soil, not exactly like the first, but closely resembling it. We may examine several other widely separated but closely similar soils that constitute upland areas in different counties and perhaps States. Inasmuch as these selected soils have well-defined or well-developed features as regards color, texture, topsoil, subsoil, etc., which definitely express the effects of climatic and biotic forces, they are regarded as *typical* soils. A vertical section, or solum slice, cut from any one of these typical soils may be regarded as a *type specimen,* and the kind of soils that the specimen represents may be called, for example, *Cecil sandy loam,* which is the name of a general concept, though limited by *typical.*

The characteristics of the typical soils examined are taken to form a concept of *Cecil sandy loam* as a type standard. Such a type standard, however, can allow the grouping of only typical Cecil sandy loams. It is plain that such a limited concept is inadequate, because like the majority of soils, most Cecil sandy loams do not have typical features. A much broader type concept is required, therefore, in order to allow unlimited application of the principle of similarity, thereby making it possible to include in the type group considered not only typical soils, but also soils that are not typical, yet which are similar.

Now let us consider briefly the similar soils that are not typical. When we examine another sandy loam soil, developed from the same kind of geologic material as that from which the typical soils already examined have developed, we find that its features vary considerably from the type standard. Although these features are very much like those of a different kind of soil, they are more like those of the typical Cecil sandy loams. The characteristics of this soil, in regard to degree of development or definiteness of its features, vary nearly 50 percent from those of a typical Cecil sandy loam; but because the variations come just within the range of similarity, this soil is also classed as *Cecil sandy loam.*

Another soil has features that approach those of a different soil; but because of its greater resemblance to "Cecil sandy loam" (concept of type standard), it is classed as *Cecil sandy loam;* and so on, until a number of typical and untypical individual soils are grouped on the basis of similar characteristics. In this manner we create general concepts, or classes, of similar soils, such as *Cecil sandy loam, Carrington silt loam,* and *Dunkirk clay.*

In nature, a number of, or a great many, similar soils usually occur together, and, on the other hand, a group of similar soils may be separated from other soils of the same type by different kinds of soils.

The law of identity. As soon as a number of individual soils are grouped according to similarity of their features and the group is given its place in the first category of our classification scheme, the law of identity is applied, and each group is given a class name that is identical for every soil of the group. To illustrate: Each individual of one group is known, for example, as a Cecil sandy loam, and this name is given because of certain *identical* characteristics that are common to all the soils of the group.

The law of identity is applied not only in naming the groups of similar soils in category I, but also in forming all the classes of the successive categories of our scheme of classification, each class being based on certain characteristics that are identical in all the soils represented by the class term.

Each class term in scientific soil classification implies a limited number of soil characteristics which must be the same in all the soils of the class; so that the class name is applied alike to all earthy bodies having these identical features. This does not mean that what we may call a Chester loam in southeastern Pennsylvania and one in Maryland are one and the same soil, any more than a Chernozem soil in Russia and one in the United States are one and the same soil. We can identify soils classed as *Chester loam,* Chernozem, etc., only by the *identical* characteristics that are implied in these class names. The meanings of these class terms are commonly known as "general concepts" or "universal concepts." This brings us to a further consideration of these general concepts regarding soils—how we create them and how we deal with them.

Function of general concepts. A soil-class term, the name of a general concept, does not designate just one individual soil, but represents, rather, many of them by reason of their common, or identical, features. In other words, a class term, such as *Miami silt loam,* or Chernozem, is a name that indicates the identical characteristics, or common features, of all the soils represented by the class term. Inasmuch as the meaning of a class name is applied alike to all soils represented by it, including both poorly and well-developed soils, variations in the identical features on which a

class is based are of no consequence, because the grouping is made in accord with the underlying principle of similarity which allows for such variations. Here attention is called to the fact that one or more identical, or common, characteristics in a group of similar soils may vary widely, inasmuch as the variation may occur in opposite directions from the type standard. To illustrate: The brown color of typical Miami silt loams may shade (within the range limited by the principle of similarity) toward the almost black color of Brookston silt loams and also, in an opposite direction from the typical color, toward the gray color of Crosby silt loams. (See table on page 203.)

Limitation of soil-class definition. There is sometimes much confusion between the description of a soil and the definition of a soil-class term. To illustrate: An individual soil may or may not be described in fullest detail, whereas a class term like *Chester loam* or Podzol must be defined by giving the characteristics that are common, or identical, to all the soils of the class. In fact, we create *soil,* likewise all other class names, or general concepts, by definition.

Meaning of the general concept, "soil." When we classify any earthy body as "soil," we recognize in it, unconsciously, it is true, certain attributes that are common to all soils in the world, and a careful analysis of this classifying process, in accord with the modern concept of soils, will show three principal common elements: (1) distinguishing characteristics (such as color, layers, and structure) that have developed to a greater or lesser degree as the result of the action of specific natural forces; (2) an inherent nature that shows not only the origin of soils from loose geologic materials, but also their "filial" relation to the loose geologic substratum materials immediately below them; and (3) the ability to support the growth of land plants. These three elements are embraced in the meaning of the general concept "soil." According to this meaning, soils are earthy bodies whose distinguishing characteristics have developed as the result of the action of specific natural forces on the upper part of deposits of loose geologic materials, which earthy bodies constitute the upper part of the outer unconsolidated layer of the earth's crust, and in which land plants grow. (Here loose geologic material means accumulated residue that results from rock weathering.)

The meaning of "soil" is fundamental in soil classification, because it implies general soil relationships that are essential in making the classification scheme a unit structure, in that the soils of the world have three elements that are common to all of them.

Defining soil types. The groups of similar soils, which are embraced in category I of our scheme of classification (such as *Penn loam, Chester loam,* and *Sassafras sandy loam*), are designated as "types," according to the American system of classification. The meaning of each name given these soil-type groups, as well as of every other class term in our scheme of classification, can be given only by naming the common, or identical, features of the soils for which a given class name stands. The type class of *Cecil sandy clay loam,* for example, can best be defined by naming the characteristics that are common to all Cecil sandy clay loams, as follows:

In forested areas (virgin) Cecil sandy clay loams have topsoils, from 6 to 8 inches in depth, that are composed of two layers—a top layer, from 1 to 3 inches in depth, of sandy-loam material that may vary in color from brown to grayish brown and which contains but little organic matter, and immediately below this a 5-inch layer of mellow sandy-clay-loam material that may be brown or reddish brown in color. Typically, their subsoils consist of hard, brittle, red clay which breaks into irregular lumps.

The above features are common to all Cecil sandy clay loams. At depths of 8 or more feet below the surface we find reddish-yellow, friable clay which contains a large quantity of mica.

General concepts; sources of error. There is considerable confusion in the use of the terms that express the various soil classes—such as *Miami silt loam, Dunkirk* (series), and Chernozem—the name being used as though it were a material soil itself, whereas the fact is that each of these terms represents many soils and merely stands for their identical attributes. In soils work, type (as a group of similar soils) is often mistaken for an individual soil; a soil series is also sometimes regarded as having materiality; and the general concept soil, as set forth in our scheme of classification (Fig. 27), has been regarded as though it were of the earth itself. In truth, *Miami silt loam* (type group) is not a soil, nor is *Dunkirk,* nor is Chernozem (they are only class names); but individual soils may be classed as *Miami silt loam,* or *Dunkirk,* or Chernozem, because of their common, or identical, distinguishing characteristics.

What is a soil? There seems to be some confusion, also, regarding individual soils—whether they exist as entities, what they are, and how they differ from soil types.

Although soils, as regarded by scientists, do not occur in nature distinctly separated from each other as are plants and animals, soil classification certainly implies the existence of soils as individual physical bodies, inasmuch as only individual things exist in the physical world, or have materiality.

A typical soil has already been defined as one that has well-developed characteristics. But this does not tell us what a soil really is, inasmuch as most soils are not truly typical. From what has been said in previous paragraphs, we can conclude that a soil is any one of the earthy bodies that constitute the upper part of the outer unconsolidated layer of the earth's crust. It is any one of the members of a group of *similar* soils, also any earthy body perceived. In terms of the nature of the thing, *a soil,* as distinguished from "soil," may be defined as a natural earthy body which is alike throughout its extent—a typical soil, for example.[1]

Similar soils by types. It is not always easy to determine the dividing line between two dissimilar soils, because they grade into each other. Nevertheless, a line must be drawn, by the aid of type standards. But it is not necessary to determine the dividing line between closely similar soils. *The problem in detail soil mapping is to group closely similar soils, and thereby show, in the midst of soil diversity, soils that resemble each other in many respects* (p. 27). On soil maps, soil types are shown by colors or hachures.

Principle of contradiction in classification. A comprehensive scheme of natural classification of soils must meet the requirements of a third law of thought called the "principle of contradiction."[2] In soil classification, this principle has to do with opposite attributes like soil acidity and alkalinity, or the prevalence of hydrogen in the base-exchange compounds in soils, as opposed to the prevalence of basic ions. In other words, acid soils imply the existence of nonacid soils. Marbut (1927) has suggested the presence of accumulated lime carbonate and the absence of any such accumulation in soils as the two major opposite attributes.

The principle of contradiction calls for two main divisions in our scheme of soil classification (two major divisions, according to

1 The term "alike" means "the same" or "nearly the same."
2 Principle of contradiction: "A thing cannot both have and not have a certain attribute."

our scheme illustrated in Figure 27) which determine the two major classes in category V. According to the law of soil genesis, the dominant soil attributes on which these two main classes are based must have developed as the result of the action of soil-forming forces on deposits of loose, or unconsolidated, geologic materials; and they cannot, therefore, be any part nor express the nature of the parent soil-forming or geologic materials.

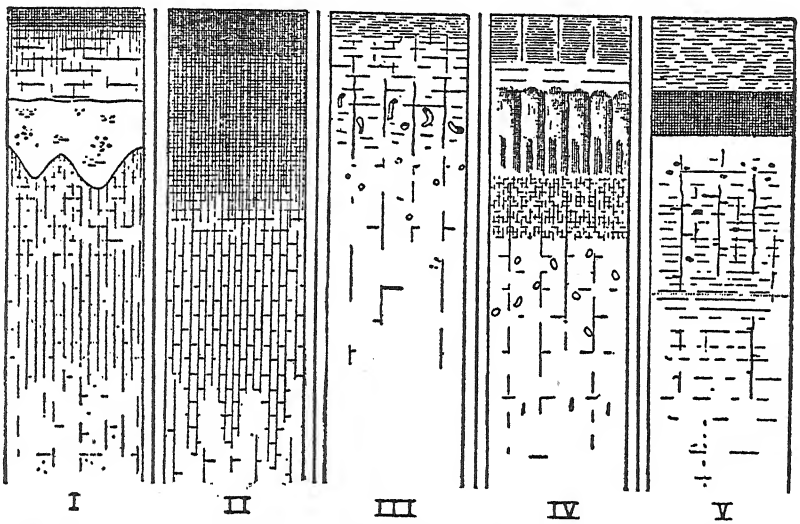

Fig. 28. Profiles of representative soils. Profile I is typical of podzolized soils of humid regions; II, of chernozems; III, of gray soils of dry steppes (*sierozem*, Glinka); IV, of alkali soils developed under arid conditions; and V, of bog soils formed under conditions of permanently standing water. (After Zakharov, Russ., 1927.)

Classification an inductive method. It is worthy of note to point out that soil classification, which is generally recognized as the first step in the development of soil science, typically illustrates the inductive method of reasoning, which is the most important mental process in the sciences. In soil classification, it operates in two principal ways: (1) In a broad way, the facts obtained in a study of a comparatively few soils regarding the factors of their formation or development, for example, are assumed to hold for all soils in the world (pp. 95 and 101). (2) Characteristics found common to a few representative soils of a given class are assumed to be the same for all other soils formed in consequence of the same soil-forming forces concerned acting under like circumstances.

The law of soil genesis. Dokuchaev (Russ.) said that if we were to consider carefully the factors concerned in the formation of the soils of a given region—such as rainfall, temperature, and vegetation—we should be able to tell in advance the nature of the soils we would find there (p. 136). He probably had in mind the law of soil genesis but did not state it (Fig. 28).[3] This law, given in the first paragraph of this chapter, expresses itself best in the soils represented by the great groups—as Podzol, Gray-Brown Podzolic, Prairie, and Chernozem—but it must also manifest itself in the closely similar soils of type groups. Inasmuch as any given class in soil classification is not based on degree of development of, or variation in, the distinguishing soil characteristics common to all the soils represented, but rather on the very same features, the law of soil genesis must concern *identical* features only, according to the law of identity.

NATURAL ORDER IN SOILS

Soil relationships may be intraregional and interregional. The former are indicated by classes that represent soils of a given region, such as those of the *Miami* series of the region of brown forest soils of the United States; and the latter relationships are indicated by world classes of soils, such as Podzol, Gray-Brown Podzolic, Chernozem, and Wiesenboden.

Intraregional soil relationships. Within a given region, natural order in soils, or soil relationship, is shown locally by closely associated similar soils, as are represented by type groups included in category I of our scheme of classification (Fig. 27 and page 147). The soils represented by each of such groups may, however, extend over only a limited area. The natural order over wider territory may be shown by classifying soils on the basis of all other attributes except texture which is included in the type groups of category I. These wider soil relationships are indicated by the classes (series) of category II. Still wider soil relationships may be established by classifying the soils on the basis of the sameness of the parent materials, as is indicated by the family groups of category III. Thus far the mechanics of classification consist in grouping similar soils into type classes, type classes into series, and series into family groups.

[3] JOFFE, J. S., and LEE, L. L. SOIL PROFILE STUDIES. *Soil Science*, Vol. 28, No. 6. 1929.

Natural Order in Soils Indicated by Soil Classes
(With Special reference to United States and territories)

Factors Responsible for Dominant Features That Determine Classes	Categories	Soil Classes	
		Soil	
Soil leaching	V	Pedalfer x. Podzolized soils y. Laterized soils	Pedocal x. Soils with lime carbonate y. Other nonacid soils
Climate (Zonal)		Tundra Podzol Gray-Brown Podzolic Red Podzolic Yellow Podzolic Reddish Brown Lateritic Yellowish Brown Lateritic Laterite Noncalcic Brown	Chernozem Degraded Chernozem Chestnut Reddish Chestnut Brown Reddish Brown Desert (Sierozem) Red Desert Shantung Brown
Prairie grasses (Zonal)	IV	Prairie Reddish Prairie	
Principally ground water and parent material (Intrazonal)		Wiesenbodens Alpine meadow soils Planosol Rendzinas Brown Forest (Braunerde) Ground-water podzols Ground-Water Laterite Bog soils Half bog soils	Wiesenbodens Alpine meadow soils Rendzinas Ground-water podzols Bog soils Half bog soils Solonchak Solonetz Soloth
(Azonal)		Alluvial soils Sand Lithosols	Alluvial soils Sand Lithosols
Sameness of parent material	III	Family groups	Family groups
All factors except texture	II	Series	Series
All factors	I	Types	Types

Family subgroups may represent soils that have formed from the same kind of parent material, but which accumulated in different manner; for example, soils that have developed from residual geologic material on steep slopes and from the same kind of material, but which had been transported and deposited as alluvium.

Robinson (Wales, 1929) proposed the term "suite" to designate such related soils. Another family subgroup, called *catena*, represents soils formed from materials of the same kind and accumulated in like manner but whose distinguishing features reflect the influences of good to poor drainage or level to rough relief. Such a family subgroup may be illustrated by three series of the Gray-Brown Podzolic group—*Miami, Crosby,* and *Brookston*—which represent forest soils in north-central United States, formed from glacial materials under conditions of good to poor drainage.

Interregional soil relationships. Beyond the family groups, natural order in well-developed soils of well-drained uplands may be traced over extensive areas, becoming regional. Such broad soil relationships are definitely expressed in the soils represented by the principal great soil groups, in which natural order is determined by those distinguishing soil features that reflect predominately the influences of climatic and biotic forces. Inasmuch as such wide soil relationships may be traced in soils in various parts of the world, represented by the great soil groups, the predominant features of the soils represented by such broad groups reflect interregional, or world-wide, soil relationships.

As regards the other great soil groups, they, too, reflect broad or world-wide soil relationships, because the soils represented, regardless of their widely scattered occurrences, have certain distinguishing features that are common to all of them. For example, wiesenbodens, wherever they occur, are related by virtue of the fact that they all have certain identical distinguishing characteristics. The same may be said of Bog soils. One can now appreciate the importance of world-wide soil relationships, inasmuch as it is such natural order that makes possible the building of scientific soil classification into a comprehensive, united whole.

Category IV. Now if one examines the tabular outline on page 147, he will find that interregional, or world-wide, soil relationships are implied in the broad classes embraced in category IV of this scheme of soil classification. Here it may be pointed out that *each category of a comprehensive scientific classification must embrace sufficient classes to represent all the soils of the world.* Such all-inclusiveness is indicated by the many broad classes listed in category IV. This category as it stands is not by any means complete. Doubtless many other great groups will be added on increased knowledge of the soils of the world.

It is to be noted that category IV is made up of three horizontal subdivisions, namely, Zonal, Intrazonal, and Azonal. When we consider the factors responsible for the development of those dominant soil characteristics that determine these three subdivisions of category IV, four stand out—climate, prairie grasses, ground water, and parent material. As regards the prairie soils (Prairie and Reddish Prairie), they are of the same climates as the soils represented by the Gray-Brown Podzolic and the Red Podzolic and Yellow Podzolic groups. Obviously, the explanation for the differentiating soil features implied in the prairie-soil classes is to be found in the influence of the prairie grasses.

The two vertical divisions of category IV, as well as of categories I, II, and III, are based largely on soil characteristics that reflect chemical qualities, namely, acidity and nonacidity. This explains why, in the tabulation on page 147, certain great groups appear in both vertical divisions. To illustrate: Some wiesenbodens are acid, others are not; some Bog soils are acid in reaction, while others are alkaline; and some Soloth soils, although presumably they were originally solonchaks (alkali), may, because of thorough leaching on permanent lowering of the water table, have somewhat acid topsoil layers. Also, in the table on pages 124 and 125, it is to be noted that some soils represented by the Noncalcic Brown or Shantung Brown group show some acidity; hence on page 147, the name "Noncalcic Brown" appears in the first column, and the name "Shantung Brown" in the other, to indicate difference in reaction.

Category V. Category V includes all soil classes in two main groups—Pedalfer and Pedocal—proposed by Marbut (1927), as suggested by two most common soil characteristics, namely, absence and presence of lime carbonate. In the scheme on page 147, the content of Pedocal is enlarged to represent also soils that do not contain lime carbonate yet which are not acid. Thus, Pedalfer represents acid soils, podzolized and lacterized; whereas Pedocal represents nonacid soils, those that contain lime carbonate and other soils that are nonacid.

Universal class. In order to show unity of the classification scheme and to indicate natural order in all soils, all the soil classes are brought together under the universal class *Soil*. For the content of this universal concept, see page 142.

Type standards. In this and the previous chapter, considerable emphasis is placed upon well-defined soil features, for the reason

that such definite characteristics, which best express the effects of whatever soil-forming factors are concerned, constitute the basis for creating soil classes. Hence, the importance of typical or representative soils in soil classification, especially in forming the groups of soils that are similar in many respects, where typical members are of the greatest value in applying the fundamental principle of similarity (p. 139). Further, in pedological studies much depends on typical soils; and in soil science, the greatest opportunities in soil-fertility inquiry are afforded by representative soils.

The unit in soil classification. One sees references to the unit used in scientific soil classification. There seems to be some confusion as to what the unit is, although some references are to soil type. Inasmuch as soil classification is a process that operates entirely within the realm of general thought and that the building blocks are classes and therefore general concepts, none of the earthy bodies concerned outside in the world of material objects can be such a unit. The unit in soil classification, therefore, must be looked for within the classification scheme itself, among the soil classes, within the realm of general concepts. As regards the mechanics in soil classification, we know that all groups above the first category are formed from lower classes. This fact drives us to category I, which embraces those classes that stand, as it were, closest to the earthy bodies in the world of material things, and hence representing them best. The members of the first category, therefore, must be the basic units. Briefly, the conclusion is that the unit of soil classification is *soil type,* not meaning an individual soil but rather a soil-type group. This fact emphasizes the importance of the soil-type classes, inasmuch as in building a scheme of soil classification, all other classes are based on these groups; and in the division procedure (p. 122), the largest and smallest land divisions made must agree with these basic units.

In conclusion. To some it may seem a hard road we have just traveled, perhaps through a wilderness; but early in soil science we are compelled to take such a course, that we may see more clearly and understand better the country that lies beyond. Perhaps the signboard was not plain; so we go back to the signboard.

What might be a sound basis for soil technology—we may ask—scientific soil classification, individual soils, or soil types? Soil classification at once drops out, for we have learned that it deals only with soil characteristics and not with soil uses. The countless

numbers of individual soils would spell confusing complexity not becoming any natural science (p. 27). Soil types, too, are out; they represent variable and inconstant members, especially changeable through use. Here constancy in nature suggests the meeting of crop requirements through the mediums of soils, regardless of kinds or types of soils. This gives an idea of what is before us in the chapters that follow. We come first to "Soil and Plant Relationships."

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PEVIEW QUESTIONS

1. Explain what is meant by natural order in soils.
2. What law governs natural order in soils? State it. Test it.
3. Describe the mechanics in building soil classification. Illustrate by use of a diagram.
4. Discuss two major principles that should guide in soil classification.
5. What is a general concept? What are they in classification?
6. Give the content of the universal concept *soil.*
7. What is the difference between describing a Chester loam and defining *Chester loam?* In describing a soil and defining *soil?*
8. What is an individual soil? How do closely similar soils occur with reference to each other? Check this in the field.
9. What is the problem in detail soil mapping?
10. What do the different colors on a soils map indicate?
11. How does soil classification illustrate inductive thinking?
12. Illustrate how natural order in soils may be shown.
13. How is soil (general concept) created?
14. Explain the difference between intraregional and interregional soil relationships.
15. What are categories in soil classification? Illustrate.
16. Discuss the importance of soil-type standards. Typical soils. Representative soils.
17. Establish what the unit in soil classification is.
18. Why have a clear understanding of what individual soils are? Soil types? Scientific soil classification?

CHAPTER 9

SOIL AND PLANT RELATIONSHIPS

Cultivation of soils for the production of food requires a knowledge of the close relation between plants and the soils themselves, as expressed in the terms "germination," "nutrition," "vegetation," "fruition," and "adaptation." The ground provides not only anchorage, but also the very materials for plant subsistence. The relation between soils and plants is best shown in the functions of the roots. These roots, the organs by means of which the nutrient element of soils are absorbed, commonly constitute half or more of a plant, and may extend far down into the ground.

Elements concerned in plant growth. Of the 92 elements occurring in nature,[1] 15 of the more important ones are commonly found in plants: namely, carbon, hydrogen, oxygen, nitrogen, sulphur, phosphorus, potassium, magnesium, iron, calcium, sodium, silicon, chlorine, manganese, and aluminum. The first 10 have for some time been regarded as the *essential elements in plant growth.* A number of other elements also occur in smaller quantities in plants, including boron, copper, zinc, iodine, arsenic, nickel, cobalt, barium, bromine, antimony, fluorine, lithium, titanium, strontium, tin, cæsium, cerium, chromium, and vanadium.

Early ideas of soil-plant relations. It is questionable whether there ever was a time when primitive people did not regard the earth as the "Great Mother" from whom came the substances that sustained life itself. When the time came for man to forsake his roving habits, he began to rely more and more on dependable sources of food to be gained from Mother Earth. He soon learned that without water the earth is barren. This idea prevailed for many centuries, and in fact it was the basis of Thales' conclusion, in 580 B.C., that plants derived all their substance from water. Historical records indicate that this point of view obtained for nearly 23 centuries later, until Woodward made his experiments

[1] Eighty-five have been officially approved (1932) by the International Committee on Atomic Weights of the International Union of Chemistry. The others require further authentication to warrant acceptance by the committee.

that proved the contrary in 1699 (Ch. 1). During the last half of the eighteenth century, Lavoisier published his refutation of the prevalent belief that water could be converted into earth by repeated distillation.

During the eighteenth century and up to 1840, the "humus theory" expressed another relation between soils and growing plants, and still another was introduced by Jethro Tull in 1731, when he published his doctrine of "horse-hoeing." Tull believed that soil particles were most important in plant nutrition. The problem as he saw it was to pulverize the earth. His observation of the successful tillage practices of the vinedressers of southern Europe, who did not approve of using dung in their vineyards, greatly encouraged him in his theory. On his own farm in England he grew 13 successive and "very good" crops of wheat on the same land without the use of any manure whatever. Tull condemned bare-fallowing as heavy and needless expense. And to him the use of manure was unnecessary, but tillage, most important. Explaining his views in a letter to the Scotland Society of Improvers of Agricultural Knowledge, he wrote:

> The only way we have to enrich the Earth is to divide it into many Parts by Manure or by Tillage, or by both. This is called *Pulveration*. The Salts of Dung divide or pulverise the Soil by Fermentation; Tillage by Attrition or Contusion of Instruments of which the Plough is Chief. The Superficies, or Surface, of these divided Parts of Earth, is the artificial Pasture of Plants, and affords the *vegetable pabulum* to such Roots as come in Contact with it. There is no way to exhaust or drain the Earth of this *pabulum*, but by the Roots of Plants. . . . Division is infinite; and the more Parts the Soil is divided into, the more of the Superficies, or vegetable Pasture, must it have, and the more of these Benefits which descend from the Atmosphere will it receive. . . .[2]

Records indicate that in later years Tull modified his views somewhat regarding the value of manure, and used on poor land, in the growing of turnips, what manure he obtained on his farm.

Plants draw on soils and atmosphere. It was the great Liebig's insight into the nature of plants that led to a true understanding of soil-plant-air relations. His hypothesis that plants took in simple gaseous and mineral substances and built them into complex organic compounds has been firmly established by subsequent physiological research. These soil-plant-air relations may be ex-

[2] Maxwell's Select Transactions, Agriculture of Scotland. 1743.

pressed as follows: From soils, plant roots absorb water and substances dissolved in it, including nitrogen and mineral elements; and from the air, plants take in carbon dioxide through their leaves. So far as the solid matter of plants is concerned, leaves gather from the air many times as much substance as do the roots from the soils.

PLANT NUTRITION AND GROWTH

The scientific explanation of plant nutrition and growth is supported by a vast accumulation of facts which may be used in discovering principles and natural laws and in improving methods of crop production. So far as they affect crop production, these facts may be considered in three periods of growth: namely, germination, vegetation, and fruition.

Germination is the beginning of plant growth. An embryonic plant becomes established in a soil by means of its roots. During the first few days of this period no acquisition of carbon dioxide from the air nor of nutrient elements from soils takes place, because sufficient food has been stored in the seeds to tide over the period required for the seedlings to establish their own food resources.

The requirements during germination are available water, favorable temperature, and oxygen. Ordinarily, light is not required; but some seeds—bluegrass and certain varieties of tobacco, for example—seem to germinate best in light.

Water for germination. Water is the first requirement of germinating seeds. It is needed for "swelling" the seeds and for life processes. Seeds and young roots take up water actively and usually with considerable force. Briggs and McLane (1907), working with a centrifuge, have shown that this force is ordinarily equivalent to about 0.001 atmosphere, or 1,000 times that of gravity. Shull (1916), working with seeds, found that in a heavy loam material with a water content of only 5 percent, seeds may exert an attractive pull for water equivalent to 1,000 atmospheres. Young or growing roots may exert a pull for soil water equivalent to from 4 to 20 atmospheres. These values represent the measurements of the equilibrium of forces between those of absorption by roots and seeds, on the one hand, and those that cause water to adhere to soil particles, on the other.

Close contact between soil material and planted seeds is ar

important factor in favoring absorption of water, and hence early germination. Accordingly, a firm seed bed is desirable for quick germination and rapid seedling growth. Probably it is for this reason, principally, that sweetclover, under dry-farming conditions, requires a hard, compact seed bed for best results. Poor contact may mean insufficient water and delayed germination.

Salts in soils commonly create such strong forces external to planted seeds and embryo roots as greatly to hinder or prevent absorption of water. Thus there is danger in planting seeds in certain alkali soils, and in placing fertilizer salts too close to planted seeds (Fig. 9).

Temperature for germination. Seeds vary in their requirements of heat for favorable germination. For example, wheat, oats, and barley require optimum temperature varying from 77° to 88° F.; maize, about 91°; and melons and cucumbers, from 88° to 99°. For semidesert summer perennials and annuals, temperatures between 100° and about 110° are required.

Successful farmers have learned by experience the relation of temperature to crop growth. Spring oats, for example, being a cool-weather crop, is planted in the spring as soon as the land is fit; whereas maize, which is a warm-weather crop, is commonly planted when air and soil temperatures are right, or as farmers express it, "when young oak leaves become nearly as long as rabbit's ears."

Favorable temperature is most important not only for water absorption but for plant life processes as well. Unfavorable soil temperature or cold soils may be caused by the presence of too much water. Good drainage, warm rains, as well as atmospheric heat, on the other hand, are important factors in the warming up of soils. "Early" and "late" soils are commonly so called because of temperature conditions.

Oxygen for germination. Oxygen is absolutely necessary in the life processes of embryo plants, and germination is impossible without this element. Any deficiency of oxygen retards the development. A deficiency may be brought about by carbon dioxide that arises from rapid decomposition of organic matter and drives out the oxygen, especially when the oxygen supply in a soil is low. Too much water in a soil may also shut out the oxygen supply.

The period of growth. Vegetation implies much activity and growth from the early seedling stage to maturity. During this

period of its development, a plant requires favorable temperature, oxygen, water, carbon dioxide, sunlight, and nutrient elements.

Temperature for growth. Favorable temperature, in regard to the atmosphere and substrata, has a most marked effect on the rate of growth, because it controls the processes on which growth de-

Fig. 29. Aëration in relation to root development and plant growth. Left—Tomato plant in solution culture that was restricted to oxygen supplied by a small bubble of air for each drop of solution that fell into the culture jar. Right—Tomato plant grown in solution culture that was continuously aërated.

pends. Best temperatures for growth are practically the same as those that are best for germination.

Three well-defined temperatures in relation to plant growth are generally recognized; these are: (1) minimum or lowest, below which growth ceases; (2) optimum, at which growth is most active; and (3) maximum or highest, at which growth is barely possible. Cannon (1923) has shown that these cardinal temperatures may be greatly modified by diminishing the supply of oxygen.

Oxygen for growth. During vegetation plants require oxygen, particularly for the roots, for oxidation and reduction. Oxidation is closely associated with the metabolic activity of plant roots.

Studies of oats, wheat, buckwheat, sunflower, mustard, peas, flax, and tomatoes have shown high requirements of atmospheric oxygen. A diminution of the supply limits the growth of roots, whereas an adequate supply favors their growth and development. Through the use of solution cultures Allison and Shive (1923) and Clark and Shive (1932) have demonstrated the beneficial effects of continuous aëration of the mediums in which plants grow upon the root and top growth of soybean and tomato plants (Fig. 29).

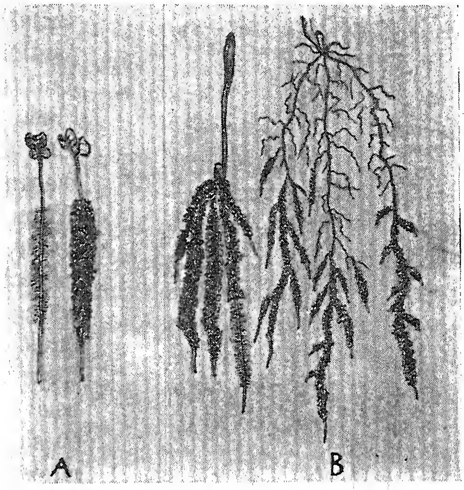

Fig. 30. The absorbing organs of plants establish very close contact with soil materials, forming soil-plant systems. A, Young mustard plants, showing soil material adhering because of root hairs. B, Wheat seedlings, showing soil material adhering to absorbing part of the root system. (After Sachs, Ger., 1860.)

Water intake. All higher plants require immense quantities of water, practically all of which is absorbed from soils through their roots. Special organs are provided for absorption, which include the tips of roots and innumerable root hairs (Fig. 30). The roots (tips) are always seeking new "feeding" grounds. Usually, only a comparatively small quantity of water is taken in through the leaves. Water constitutes from 75 to 90 percent of the weight of green plants. In addition to this requirement, enormous quantities pass up through them and evaporate from the leaves.

Water is one of the essentials for all life processes. Some of it is decomposed into its elements in plants and these elements become fixed in the tissues. Furthermore, all chemical processes within plant cells take place in water mediums. If, because of desiccation of a soil, the water mediums in the cells of a plant diminish to a point that causes permanent wilting, or below, death of the plant ensues. When this happens, the force that is exerted by soil particles in retaining a small quantity of water becomes equal to or

less than the absorption power of the roots. According to Breazeale (1930), the adhesive force of the dry soil material (attraction for moisture films), which may cause water within the plant to move outward, may equal an enormous pull of 25,000 atmospheres.

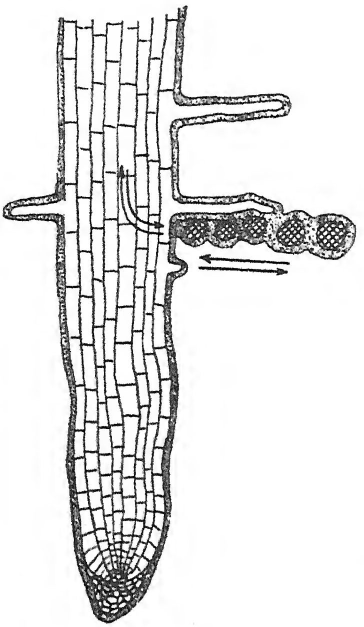

Fig. 31. Equilibrium between the suction force within a plant root and the adhesive force exerted by soil particles for film water, which results in no movement of water. (After Breazeale, 1930.)

Under normal moisture conditions, the suction force within the plant roots is greater than the external retentive force of the soil particles. Inasmuch as the forces tend to balance, or come to an equilibrium, water ordinarily moves into the plant, thus maintaining the water mediums within the cells. When a soil contains available water, the adhesive force of the soil particles is greatly reduced, diminishing with thickening of the water films. But whenever the suction force within the roots and the adhesive force of the soil particles outside come to equilibrium, no movement of water takes place, as is illustrated in Figure 31.

A growing plant gives off water continuously in the process of transpiration. If the rate of absorption does not keep pace with transpiration, the water content of the plant diminishes, and the plant wilts. Briggs and Shantz (1912) have designated the moisture content of a soil at which a plant permanently wilts as the *wilting coefficient*, which, they have observed, varies but little with different agricultural plants for a soil of a given texture. The equilibrium between the forces of water absorption and transpiration within a living plant is not merely mechanical; it involves life processes that are associated with living protoplasm, in which oxygen plays an important role.

Plants classified on water relations. Plant species differ not only in their water requirements, but also in their adaptation to water conditions. Some plants are so constituted that they can

tolerate an abundance of soil water, like marsh and low-meadow plants; whereas others can endure limited moisture, like those that inhabit arid and semiarid districts or regions. Plants that are characteristic of perpetually moist habitats, such as areas bordering bodies of water or in moist tropical forests, are classed as "hydrophyte," while those of dry habitats are classed as "xerophyte." Most plants are suited to temperate climate and moderately moist habitats. These intermediate types, including most crop plants, are classed as "mesophyte."

Physiological drought. The plants that grow in soils that are rather heavily charged with salts, as in salt marshes and on alkali soils, are called "halophytes." Asparagus belongs to this class. Most crop plants cannot tolerate the presence of much salt. Owing to the fact that considerable salt in soils may interfere with water absorption, plants under such conditions may wilt and die. This may happen when seeds are planted in strongly saline or alkali soils, when too great a quantity of fertilizer salts is applied too close to seedlings, and when highly concentrated solutions of nutrient salts are applied to potted plants. Under such conditions the plants are said to suffer from "physiological drought."

The water problems in crop production are discussed in Chapters 12 and 13.

Carbon intake. For many years it was thought that plants obtained all their carbon from the carbon dioxide ordinarily contained in the atmosphere, and that soil substances were unimportant as sources of this element; but Lundegardh (Swed., 1924) has found that the carbon dioxide originating in aërated soils from the decomposition of organic matter is a much more important source of carbon than the atmosphere, whose average content of carbon dioxide, according to Clarke (1924), is about 3 volumes in 10,000 (0.029 percent). According to Stoklasa (Czech., 1927), carbon dioxide occurs in soil solutions as bicarbonates, and is absorbed by roots as CO_3 ions along with other essential elements.

The carbon dioxide of the air is taken in by crop plants through innumerable minute openings or pores (stomata), most of which usually occur on the under surfaces of their leaves.

Sunlight and photosynthesis. Sunlight is indirectly essential to the existence of green plants, because without it their leaves cannot function. Blackman (Eng.) has referred to green plants as the

"foundation stones in the scheme of living things." All animals, including human beings, are directly or indirectly dependent for their food on the manufacture, within green leaves, of food substances out of carbon dioxide, water, and nutrient elements. This manufacturing process is made possible through the action of sunlight, hence the term "photosynthesis." Photosynthesis, or carbon assimilation, is a fundamental process which is associated with certain pigments that absorb the energy of sunlight. The energy thus obtained is used in forming carbohydrates (sugars, starches, celluloses, etc.) from carbon dioxide and water, and in making complex nitrogenous compounds. During photosynthesis, oxygen is evolved, according to the following equation:

$$6CO_2 + 6H_2O + \text{Sunlight} = C_6H_{12}O_6 \text{ (glucose)} + 6O_2$$

The above equation does not represent the actual transformation process, but shows rather the exchange of carbon dioxide and oxygen, and a first product, glucose. Scientists have yet to discover a green leaf's secret of converting carbon dioxide and water into carbohydrates through the action of sunlight.

Evidence indicates that the energy necessary for decomposing carbon dioxide is absorbed by the green pigments (chlorophyll). Sachs (Ger., 1862) was the first investigator to link the presence of carbohydrates in the leaves of green plants with assimilation of carbon. In this process white light is best. The red rays are much more effective than the blue rays. Photosynthesis depends mainly upon the red-yellow part of the spectrum. According to Brown and Escombe (Eng., 1905), a large part of the energy absorbed from sunlight is used in plant transpiration, which is an important factor in the absorption of carbon dioxide.

Other light relations. Artificial light, also, seems to have possibilities for stimulating plant growth. Most crop plants seem to be long-day types. Chrysanthemums and poinsettias require less light, and are representatives of the short-day types.

Cooper (1929-1930) has obtained data which suggest that plants like Kentucky bluegrass, alfalfa, sugar beets, and maize which require fertile soils and hence an abundance of strong nutrient ions like NO_3^-, $H_2PO_4^-$, K^+, and Ca^{++} for optimum growth also require light of high quality. Many plants like the fescue, sweet vernal, and poverty grasses which grow normally on poor acid soils and which can endure quantities of weak ions like SiO_3^{--}, Al^{+++},

and Fe^{+++} are commonly tolerant of shade, and can grow very well under this condition. But such plants have low food value.

The carbon cycle. Carbon assimilation by plants is a most important stage in a cycle that includes both fixation and liberation of carbon. The carbon fixed by plants is utilized as a great source of energy. Whether in the body of a living organism or in ordinary combustion, the union of oxygen with carbon generates energy or heat. The carbon dioxide (liberated carbon) thus evolved finds its way again to the leaves of green plants, where it is once more fixed or converted into food materials—and so on, in a perpetual cycle.

Intake of mineral elements. When a plant is burned, ashes, or mineral substances, are left. In the burning, such elements as carbon, nitrogen, chlorine, and considerable sulphur escape as gases. Compared with water or carbon consumed by plants, the quantity of mineral which roots take in is not large. One bushel of Indian corn or wheat, for example, contains only about 1 pound of ash.

Intake of nitrogen. In addition to carbon dioxide, water, and minerals, plants take up other elements, including nitrogen, sulphur, and chlorine. Of these three elements, nitrogen is by far the most important. Although the nitrogen intake is rather small, its importance is due to the fact that it is an indispensable part of protein which, in turn, constitutes a vital part of protoplasm.

Boussingault (Fr., 1855) was the first scientist to point out that higher plants cannot utilize molecular or free nitrogen (N_2), despite the fact that their leaves are immersed, as it were, in a gaseous mixture (air) of which nearly four fifths (by volume) is nitrogen. Boussingault drew his conclusion from nonleguminous plants, but stated that leguminous crops behaved abnormally. In later research, he established the same fact for legumes. The fact is that crop plants obtain their nitrogen through their roots from nitrogenous compounds naturally contained in soils, from nodule bacteria (in case of legumes), and from substances supplied as fertilizers.

Laws governing intake. The young parts of roots, including the root hairs, do most of the work of absorbing water and nutrients. That this is active rather than passive absorption seems to be indicated by the structure of the absorbing organs and the enormous number of root hairs that are engaged in the work.

or major elements, growth is in a large measure proportional to the supply, and comparatively large quantities are not only tolerated but necessary. The trace-requirement elements, on the other hand, cause increased development only when they are available in very small quantities. For example, Haas (1930) found that, in

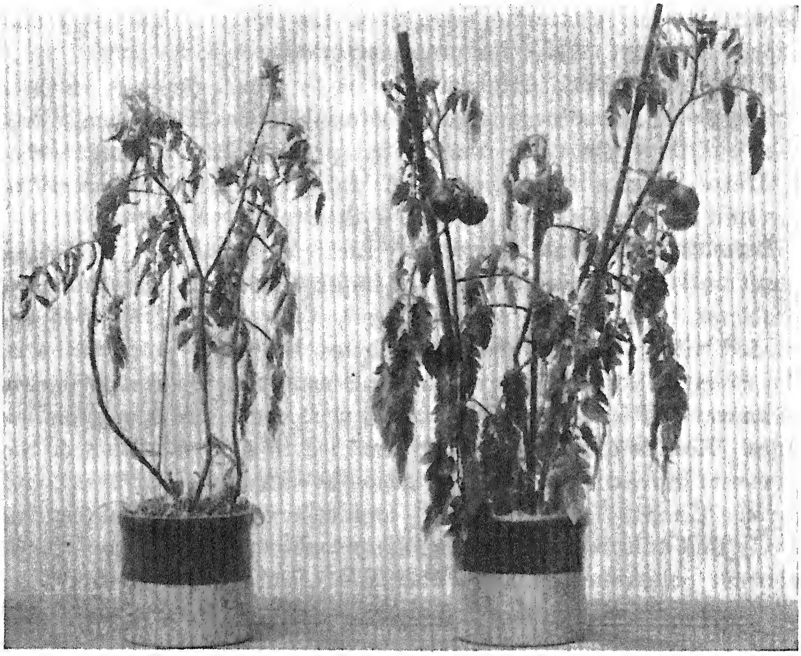

Fig. 32. Manganese is an essential element in plant nutrition, as shown by tomato plants grown in soil material that represents a manganese-deficient soil of Florida. Left—Chlorotic plants with complete fertilizer, but no manganese. Right—Normal growth with complete fertilizer plus manganese. (U. S. Dept. Agr.)

California, a small quantity of boron was injurious to citrous plants, but when it was present in smaller quantities (0.2 part per million), it proved to be essential for healthy growth.

Nutrient elements, distribution and functions. A general knowledge of the distribution, supply, and functions of the essential nutrient elements may prove to be helpful in appreciating the problem of plant nutrition and fertilization.

Nitrogen (N), a colorless, odorless, tasteless, and inert gas, has its origin in the atmosphere. By volume, nitrogen is 78 percent

of the air, and by weight, 75.5 percent. Only in combination has this element the ability to support life. As a soil constituent, nitrogen occurs in three principal forms; these are: insoluble organic compounds, soluble nitrates, and ammonium compounds.

The importance of nitrogen is seen in the stunted growth, poor crops, or absolute failure that results from an insufficient supply. A common symptom of nitrogen deficiency is a general yellowing of the leaves and stalks, as is shown, for example, when a field of young grain or Indian corn remains covered with water for a rather long period of time. In winter wheat, nitrogen deficiency has been found to cause "yellow-berry," or starchy kernels. In fruit trees, a lack of nitrogen has been found to delay opening of the buds, to reduce the number of blossoms, and to cause the leaves to turn yellowish green.

Phosphorus (P), in pure elemental form, is a white, nonmetallic, waxy solid; but it occurs in nature only in combined forms, being widely distributed as phosphates. Soils contain comparatively small quantities of this element. It is commonly expressed as phosphorus pentoxide (P_2O_5) which is erroneously called "phosphoric acid."

The functions of phosphorus in plants are similar to those of nitrogen and sulphur. It enters into the composition of nucleo-proteins and other indispensable protoplasmic substances, some of which seem to bear vital relation to the osmotic properties of plant cells. Loew (1899), a German scientist working in America, showed that phosphorus is essential for cell division, and Reed (1907) has found that it is required in the transformation of starch into sugar.

As a growth element, phosphorus is an important factor in root development, ripening processes, and in the development of grains or kernels. A deficiency of this element is shown in stunted growth and commonly in comparatively slow ripening, depressed yields, under-weight grain, and lowered feeding value of produce. In fruit trees, a deficiency causes delayed opening of the buds, and reduces the number of blossoms.

Potassium (K, from *kalium*) is a metallic element which is classed as an alkali. Although it is never found free in nature, its salts are abundantly and widely distributed. Some soil materials like clay are comparatively rich in this element. In plant ash, like wood ashes, it occurs as soluble carbonate which may be

easily leached out, hence the origin of the term "potash." This element is commonly expressed as K_2O which is called "potash."

Potassium seems essential in the vital activity of protoplasm. It is regarded as an important aid in the manufacture of carbohydrates and proteins. Nobbe (Ger., 1870) showed that when potassium salts are withheld, starch manufacture abruptly ceases. Reed (1907) found it necessary in cell division. The role of this element in plant nutrition is not well understood.

The importance of potassium in plant nutrition is associated not only with assimilation of carbon dioxide, but with utilization of carbohydrates as well. The relationship between potassium and nitrogen is shown by the fact that the full effectiveness of one depends on a particular quantity of the other. In many plants, under certain unbalanced conditions, potassium restores the proper balance between carbohydrates and nitrogen. Symptoms of potassium deficiency in plants are given in Chapter 22.

Calcium (Ca), one of the metals, is the fifth most abundant constituent of the earth's crust, but it does not occur in nature uncombined. It is one of the so-called "alkaline earths," and is the principal element concerned in the reaction of soils, particularly in humid regions. The name by which it is commonly known is "lime" (CaO), which has from remote ages been regarded as an elementary earth. It is an important constituent of limestones, marbles, corals, natural chalks, and shells.

Calcium, like potassium, occurs in plants principally in the leaves. One of its important functions consists in neutralizing toxic oxalic acid which forms in many plants as a by-product in metabolism. Another of its functions is the building of proteins. Evidence seems to indicate that it plays an important role in plants in association with magnesium, under certain conditions preventing magnesium toxicity. But little is known of its specific role in the life processes of green plants. It seems to function also in preventing the solution of cell walls and in rendering the cell walls of absorbing roots less permeable to some other ions, while it makes physiologically available certain of the nutrient elements. Calcium cannot be replaced by barium nor by strontium.

Magnesium (Mg) is a most abundant, metallic element, closely associated in nature with calcium. It occurs principally in the forms of silicates, carbonates, and chlorides, as micas, talc, asbestos, meerschaum, dolomite, dolomitic limestone, carnallite, and

kieserite. Magnesia (MgO) was confounded with lime (CaO) until 1755, when Black (Scot.) showed that they were quite different. Magnesium compounds commonly occur in soils, resulting from decomposition of rock-forming minerals. Soils developed from geologic materials derived from serpentine rocks may be nonproductive, owing to an excess of magnesium. On the other hand, there are soils that are unproductive because of magnesium deficiency.

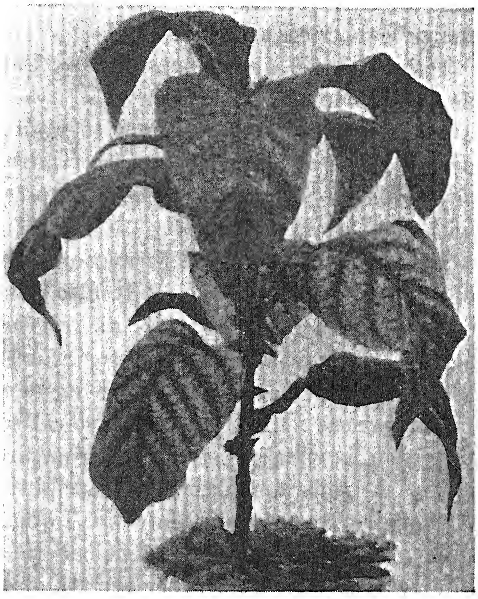

Fig. 33. A tobacco plant showing characteristic symptoms of magnesium deficiency. Light-green or almost white color progresses from the tips toward the base of the leaves along the margins and between the veins. (Bur. Plant Industry, U. S. Dept. Agr.)

In plants, magnesium occurs principally in young organs and seeds; this is likewise true of potassium. Thus its functions, in part, may be similar to those of potassium. In plant metabolism, this element seems to serve as a carrier of phosphorus. Although an important constituent of chlorophyll, it ultimately moves into the seeds; herein it differs from potassium and calcium.

Inasmuch as magnesium is an important part of chlorophyll, indications of deficiency of this element in plant growth are to be looked for in the appearance of the foliage, which shows a chlorotic condition when there is not sufficient magnesium present. A deficiency causes "bronzing" of citrus leaves.

Crop plants absorb magnesium from soils at the same rate throughout the growing period, and this element is required from the early seedling stage to the late growth period (Fig. 33).

Sulphur (S), a nonmetallic element, commonly called "brimstone," has been known from remote times, and was regarded by alchemists as the principle of combustion. It is abundantly dis-

tributed in nature both as an element and in compounds. Much sulphur exists in coal and petroleum.

Seed-forming plants can use sulphur only in the form of sulphate. Sulphur enters into the building of protein compounds, but here it has never been found in union with oxygen. Alfalfa, soybeans, cabbages, cotton, onions, rutabagas (Swedish turnips), and turnips take up considerably more sulphur than do crops like maize, oats, rice, and wheat.

Sulphur and phosphorus are as important in plant nutrition as are carbon and nitrogen.

Iron (Fe), although second to aluminum in abundance, rarely occurs in the free state. Plants require comparatively small quantities of this element, yet most soils are most abundantly supplied with it.

Iron is essential in the formation of chlorophyll, but it does not enter into its composition. It also acts largely as a catalyzer in oxidation processes; that is, its presence accelerates chemical reaction. Lack of available iron or a deficiency of active iron within plants causes chlorosis, or yellowing of the leaves.

Manganese (Mn), one of the so-called "rare elements" in plant nutrition, is widely distributed in nature, commonly in small quantities. In soils and plants its distribution is less than that of iron. Although plants require only small quantities of this element, some soils have been found so deficient in available manganese as to hinder or prevent the proper growth of crops.

Manganese seems to function as a catalyzer in the oxidation processes that are concerned in growth. Kelley (1912-1914) has found that it also tends to control the absorption of calcium and magnesium. McHargue (1926) has concluded that manganese is also closely associated with chlorophyll formation and carbon assimilation. Chlorosis and poor plant growth are the common effects produced by a deficiency of this element (Fig. 32). Manganese cannot fully take the place of iron in plants; nor iron, manganese.

Boron (B) is a nonmetallic element which occurs in nature in various borates (borax, for example) and in the form of boracic (boric) acid. This element is required by plants in extremely small quantities. Its function is regarded by some physiologists as catalytic; by others, as a simple nutrient. Strong roots and shoots develop because of it. A lack of it results in abnormal conditions within plants. In tomatoes, it has been found essential for

normal growth and for the formation and development of fruit. Inquiry at Rothamsted, England, has shown that in the horse or broad bean, boron is absolutely necessary in the production of ducts that conduct nitrogenous substances from the nodules, and sugar and other food material to the nodule bacteria. It also aids in the intake of nitrogen, potassium, and calcium, especially calcium.

Silicon (Si), next to oxygen, is the most abundant and widely distributed element. It occurs in practically all soils as silica (SiO_2). Plants accumulate considerable quantities of this element in their cell walls. For example, the straw that is required to produce 45 bushels of oats and 30 bushels of wheat may contain, respectively, as much as 40 and 46 pounds of silicon. Although mostly superfluous in plants, this element seems to serve in strengthening cell walls and thereby stiffening the straw and stems. Only a very small quantity is really essential. Its function in life processes is not known.

Copper (Cu) is widely distributed in nature. In ores it occurs as native copper, sulphides, and carbonates. It also exists in such compounds as arsenates, phosphates, sulphates, and silicates. Minute traces are often detected in igneous rocks and in very small quantities in sea water. It occurs in most soils; in some a deficiency has been shown by stunted growth and crop failure.[4]

Sodium, chlorine, and aluminum. Sodium, although always present in plant tissues, is not regarded as essential to land plants; but in the life of marine plants, it plays a very important role. Some investigators believe that sodium is of more or less physiological importance to plants, especially in its association with potassium.

Chlorine is not included in the list of essential elements; yet with some plants like tobacco, an adequate supply has been found necessary for best growth and quality.

Aluminum, according to Mazé (Fr., 1915) and others, is regarded as an important element in plant nutrition, for it seems to play a prominent role under natural conditions. Green leaves are comparatively rich in aluminum, in which it seems to be associated with the chlorophyll.

Dual work of green plants. Green plants alone possess the power of manufacturing food materials. They constitute the im-

[4] See under Copper in Index.

mediate contact between nonliving and living things. Out of carbon dioxide, water, nitrogen, and mineral elements they fabricate food substances for their own use, and directly and indirectly provide food for all animals. Inasmuch as plants depend directly on the activity of soil micro-organisms for a large part of their carbon, it may be said, according to Stoklasa (Czech., 1927), that the carbon dioxide that is discarded by bacteria as a by-product of their life processes comes to a man's table as his daily bread.

Plant food v. fertilizing elements. Commercial fertilizers and their constituents are commonly called "plant foods." In the strict sense, they are not foods at all, but rather materials that provide certain elements that are essential in the manufacture of plant foods. Carbon dioxide, water, and the essential nutrients are the raw materials that green plants use in making carbohydrates, fats, and proteins which, in turn, constitute both plant and animal foods. Terms like "fertilizing materials," "fertilizing elements," "plant-food elements," "fertilizer constituents," "elements of plant food," and "nutrient elements" have been suggested as better terms to use in connection with fertilizers.

Fertilizers useless without green leaves. The utilization of fertilizing elements by crop plants depends on the presence of green leaves. If bluegrass, for example, is fertilized and then kept defoliated by very close clipping, no benefit can result, owing to the fact that the food factories (leaves) have been destroyed. On the other hand, if the defoliated grass is allowed to grow, the growth up to a certain point will be made at the expense of the food reserves within the roots. When sufficient leaf area develops, however, synthesis of carbohydrates and protein and utilization of the added nutrient elements begin. Accordingly, too close and frequent cutting of lawn grasses may prove to be harmful.

Other leaf relations. What has been said regarding the effect of defoliation suggests a method for killing such weeds as quackgrass (quitch grass), Canada thistles, and brakes (ferns). The practice of poisoning potato bugs and all other leaf-eating insects has a scientific basis; likewise the deprivation of sunlight and the use of "shade crops" in killing weeds. There is a scientific reason why clover, alfalfa, and other grass seedlings commonly fail when planted in the same field with small grains that attain a heavy growth, particularly when the grain lodges. Applying the nutrient element nitrogen in a solution of nitrate of soda, for example,

to roots of rhubarb in a dark forcing cellar would prove to be useless, because of the lack of sunlight which is necessary in converting the nutrient elements into plant food. Moreover, a weak growth in shade or during prolonged cloudy or rainy weather may be the result of insufficient photosynthesis, resulting from a lack of sunlight.

Importance of healthy plants. Plants do not passively absorb the raw materials that they require. On the contrary, they consume vital energy in so doing. Thus it is necessary that crop plants be surrounded by favorable conditions or a healthful environment to enable them to perform their important task. Usually, the greenest and healthiest plants grow best and do the most efficient work.

Organic substances as nutrients. During germination and, in very young seedlings, during the period when the manufacture of food substances in the plants has not yet begun, nutrition consists in utilization of food materials that have been stored in the seeds. But when the plants develop green leaves, they make their own food materials from the simple substances that they take in through their leaves and roots.

Roots of crop plants do not seem to be able to absorb organic food substances that have high molecular weight, although Boehm (Ger., 1883) and others have shown that various sugars and other organic compounds, such as mannite ("manna sugar"), amides, and amino acids, can be absorbed by higher plants, and that they serve to nourish them. One of the curiosities of nature is that certain plants, including pitcher plants, sundews, and Venus's-flytraps, feed on insects.

Experiments in nutrition of higher plants, in which organic materials have been used, have led to the conclusion that such artificial feeding is far inferior to the method of plant nutrition that nature has provided.

It has been pointed out on indirect observations that certain vitamin-like substances are also essential for plant growth, but it remains to be proved whether vitamins are active principles in plant nutrition. Also, there seems to be evidence which indicates that certain organic substances, such as may occur in manures, may have direct beneficial effects on plant growth.

Intimate contact between soils and plants. Plant roots establish very close contact with soil materials by means of their feed-

ing roots and tiny root hairs. This may be seen when, for example, a young radish plant is pulled out of a garden soil. The young roots do not come out clean nor easily, but are completely covered with soil material which adheres so firmly that it is practically impossible to wash it off without injuring the tissue (Figs. 30 and 34). Liebig (1858) and Sachs (Ger., 1860) pointed out the significance of this "growth fusion" in enabling roots to dissolve sub-

Fig. 34. The relation of root hairs to soil mediums. hh, Root hair. e, Part of main root. 1, Air space in soil medium. 2, Soil particles. 3, Water film adhering to soil particles. (After Sachs.)

stances that are ordinarily insoluble. The dissolving agent is carbonic acid (H_2CO_3) exuded by the roots, as was shown by Czapek (Ger., 1896). This root action depends on the soil solution which is usually regarded as the connecting link between the soil mass and the underground absorbing system of plants. According to Hoagland and co-workers (1939), immediate contact between roots and soil colloids effects contact exchange of ions which makes possible ion depletion as well as ion accumulation in roots.

Root systems and "feeding power." The root systems of plants differ greatly, depending on several factors, including species, rainfall, irrigation, drainage, supply of available nutrients, soil reaction, and physical condition of the environment. Under like conditions, some plants root deeply, whereas others, like squashes, spread their roots laterally and widely within the surface 1-foot

zone. Some root systems are coarse and open, whereas others consist of masses of fine, fibrous roots.

The ability of roots to obtain nutrient substances also varies greatly. Truog (1922) has pointed out that this difference cannot be explained wholly by the quantity or kind of acid that is excreted by roots; the chemical forces within the plants and around their feeding roots may also effect a controlling influence.

Fruition. Plant growth does not continue indefinitely. After a certain time, which varies according to species, growth slows down and finally stops, marking the beginning of the fruition period.

During fruition, a crop plant matures, and in so doing produces its fruit or seeds. This is not a period of food synthesis, but rather of translocation of food materials from the stems and leaves into the necessary constituents for reproduction. Only oxygen, water, and favorable temperature are required during this period. During the ripening stages or late maturity, transpiration of water exceeds absorption, so that plants gradually dry and finally die; particularly is this true of annuals and crop plants.

CROP ADAPTATION

Plants have adapted themselves to all climatic and soil conditions except those of salt deserts. This includes plants that grow in ponds and shallow lakes, for they, too, have their soil "preferences" almost as marked as those of land plants. On the other hand, some plants are almost cosmopolitan, like the common reeds.

Grasses, which usually have an abundance of fine fibrous roots, can obtain their requirements best in the heavier-textured soils. The same holds true for wheat. Some plants, such as asparagus, greasewood shrubs, and saltgrass, are able to grow in wet saline and alkali soils (Fig. 35); and some, like sagebrush shrubs and cacti, can endure arid and semiarid conditions. There are plants that can satisfy their wants on sand dunes. Again, certain plants like blueberries (*Vaccinium* spp.), cranberries (*Oxycoccus* spp.), rhododendrons, and heaths exist only on lime-poor or acid soils; whereas other plants like sweetclovers (*Melilotus* spp.), alfalfa or lucerne (*Medicago sativa*), and tamaracks (*Larix laricina*) thrive best on soils that are rich in lime.

Climate and plant adaptation. Under natural conditions, climate (including temperature and precipitation) is the principal factor in determining the kinds of plants that naturally inhabit a

given region, or which determine so-called "climax" vegetation. Hence the development of different kinds of vegetation, such as tundra, tropical, deciduous forest, chaparral, grassland, pine-fir forest, sagebrush, desert-shrub, semidesert grassland, maple-beech, pine-hemlock, oak-hickory, and palouse. Other factors that influence the development of types of vegetation include those classed as edaphic, biotic, and topographic. Facts like those mentioned

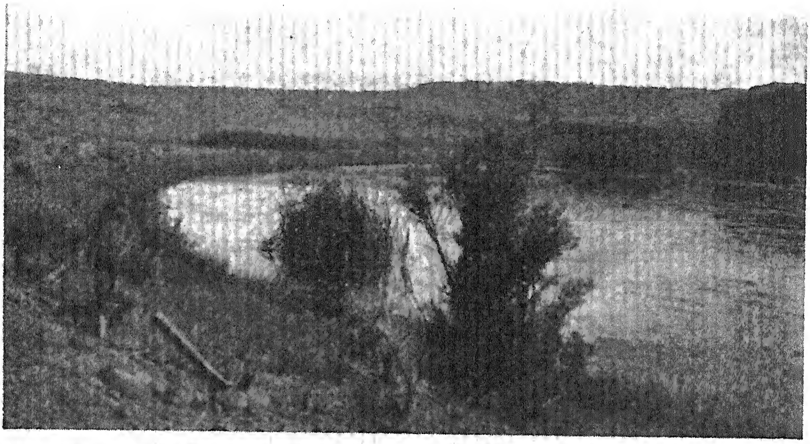

Fig. 35. A study in natural plant adaptation, in a semiarid district of central Washington. In the saline water of the small pond are cattails and tules; along the moist shore, in a 16-foot zone, are greasewood shrubs and saltgrass; and on the surrounding uplands, sagebrush shrubs.

have established the principle of plant adaptation which may be profitably applied in agriculture.

Adaptation of crop plants. The influence of climate on adaptation of crop plants may be well illustrated by cotton, which may be grown successfully on nearly every kind of soil, excepting deep sand and very hard, compact clays; yet in the United States, for example, its production is limited principally to the southern States, regardless of the character of the soils.

In regard to the influence of both climate and soils on adaptation of crop plants, the agricultural regions of the United States and of other countries afford especially interesting subjects for study (Figs. 20, 21, and 36).

In a given region and even on individual farms one may observe interesting examples of adaptation of crop plants. For example,

Cooper and associates (1929) have found that in New York red fescue grass (*Festuca rubra*) is restricted mainly to the Champlain Valley, and that colonial bentgrass (*Agrostis tenuis*) favors comparatively moist and cool situations. Adaptation of other crop plants to climate and soils is given in Chapter 23.

Adaptation important in farming. An important factor in successful crop production on a given farm is the growing of those

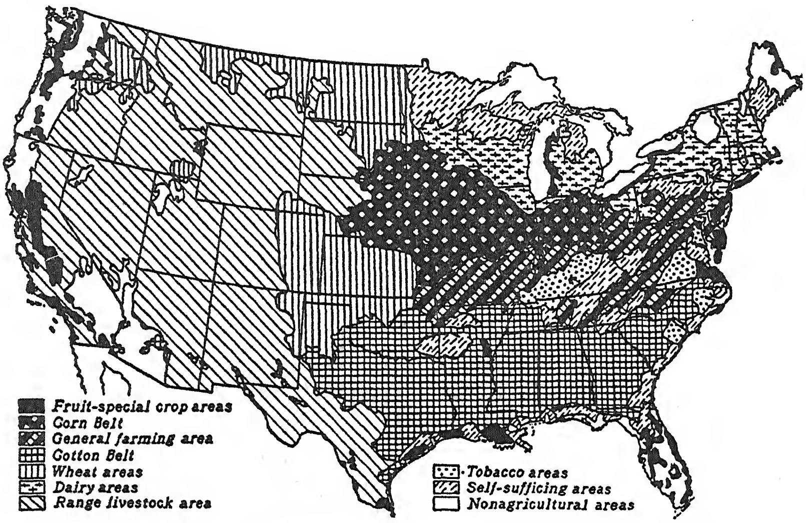

Fig. 36. Major types of farming in the United States. (U.S.D.A.)

crops or varieties that will give the best returns under the conditions peculiar to the land. Long ago the Romans appreciated the adaptability of crop plants, and on this basis they classified their lands. As early as 1645, Sir Richard Weston (Eng.), on observing the successful practices of the Flemish farmers, formulated such a definite statement of this cardinal principle of husbandry that it may still serve as a practical guide in farming. While in Flanders he wrote in his "Legacy" to his son:

> It is a certain thing, that the chiefest and fundamentallest point in Husbandrie, is, To understand the nature and condition of the Land that one would Till; and to sow it with such Seed as it will produce, either Naturally, or by Art, that which may turn to a Man's greatest profit and advantage.[5]

[5] WESTON, SIR RICHARD. THE HUSBANDRIE OF BRABANT AND FLANDERS, in Hartlib's Husbandrie. 1645.

Native plants may indicate character of soils. The growth of native plants has long been used as an indicator of the suitability of "new" land for agricultural purposes. This practice undoubtedly originated with primitive husbandmen who used trees, principally, as indicators. This old custom was common in Roman times, continued to colonial days, and it is still useful. Agricultural values of lands are commonly expressed by descriptive terms like "maple-and-walnut land," "chestnut soil," and "jack-pine land."

As late as about the middle of the nineteenth century big-tree growth was a common criterion for judging suitable agricultural lands. During the early settlement of southern Wisconsin, for example, some excellent long-grass prairie areas were avoided, because it was thought that any land that naturally produced only grass was not suitable for anything else; but the settlers who came later, finding timbered lands already occupied, reluctantly took up the unoccupied prairie land, thereby discovering their great agricultural value.

According to Shantz and Piemeisel (1940), large, bushy sagebrush indicates land well suited for irrigation farming; whereas very poor growths of shadscale and sagebrush shrubs indicate rather poor soils. Both saltgrass and pickleweed lands are wet and saline, and need drainage and leaching before cropping.

The Corn Belt was formerly characterized by tall bluestem (*Agropyron*); while the spring-wheat region was characterized mostly by tall wheatgrass (*Agropyron subsecundum*). The spruce-fir lands of the southern lowlands have little or no agricultural value, whereas areas on which the natural vegetation consisted of cypress, tupelo, and red-gum trees have been found very suitable for farming.

SOIL EXHAUSTION

From the earliest records pertaining to husbandry, one might conclude that primitive peoples early learned that continual cropping exhausted their cultivated lands. Their ideas of exhaustion were "to wear out," "to have crop-producing strength fail," and "to tire." It was logical for them, when crops failed, to think of Mother Earth as losing her crop-producing strength. Experience taught them that they were right, for they found that reposing or taking land out of cultivation beneficially affected their yielding power.

Only a few regions or districts of exceptional, naturally fertile soils can be cited to illustrate an enduring agriculture without recourse to manures or other fertilizing materials. These are: the Valley of the Nile, the slopes of Vesuvius, and the plain of Hauran east of the Jordan which has produced bountiful harvests of wheat for many centuries.

Farmers down through the centuries have had experience of soil exhaustion. Xenophon (Gr.), about 400 B.C., must have seen exhausted fields, for he wrote: "If we continue to sow for a long Space the same Sort of Grain upon any Ground, . . . it will impoverish the Ground, and wear it out of Heart." [6]

Lucretius on soil exhaustion. In his meditations about the world growing old, Lucretius (98-55 B.C.), one of the greatest of Roman poets, wrote the following suggestive lines:

> She brought forth Herbs, which now the feeble Soil
> Can scarce afford to all our pain and toil.
> We labor, sweat, and yet by all this strife
> Can scarce get Corn and Wine enough for life.
> Our Men and Oxen groan, and never cease,
> So fast our labors grow, our Fruits decrease.
> Nay oft the Farmers with a sigh complain
> That they have labour'd all the year in vain.[7]

Some early causes of barrenness. Out of the early experiences of the Flemish farmers (p. 16) came this maxim: "No forage, no cattle; without cattle, no manure, and without manure, no crop."

The early English farmers, too, had their soil-exhaustion problems. Blith (Eng., 1652) gave the following causes of barrenness: "In Man himselfe, In the Land itselfe." "Tilling Land till it bears no Corn." "Mowing Ground till it Graze no more, or yield no Grasse."

Soil exhaustion in America. Early settlers found in America soils that were very much like those of western Europe, from whence they came—light-colored forest soils of comparatively low producing power. But the American soils were virgin, and here there were wide expanses of unoccupied lands. Many of these virgin soils were originally highly productive; but when little or no effort was made to maintain their producing power, their exhaustion was inevitable. Big-tree growth was the only criterion

[6] BRADLEY, R. Œconomics of Xenophon. Translation. 1727.
[7] SIMKHOVITCH, V. G. HAY AND HISTORY. Political Science Quarterly, Vol. 28, No. 3. Sept., 1913.

the colonists knew in judging the fruitfulness of these new lands. Cutting and burning of forest trees, exhaustive cropping, turning of abandoned fields into commons, and clearing and cropping of more new land are common chronological items that may be found in the records of the early settlements.

It was a common practice in those days to classify soils according to the number of continual crops they would produce before they became exhausted: for example, 10- and 4-crop lands. Despite the destructive practices of the early settlers, the colonial farmers were most prosperous. Nevertheless, it was a period of soil exhaustion. In Virginia and Maryland, for example, thousands of acres were abandoned and turned into commons. Farmers or planters, whose exhausted lands were covered with mortgages and whose debts pressed heavily upon them, felt the call of the western frontier, and began emigration to the new country beyond the Ohio River. By 1790, the emigration had increased to such a degree that it caused great alarm to those who had concern for the future welfare of the United States. In the South, as in South Carolina, farming "was characterized by failure to diversify crops, little attention to systematic rotation, shallow ploughing, and meagre use of manures," which led to general soil deterioration.

In the Patent Office Report for 1841[8] may be found this significant statement regarding agricultural conditions: "In the year 1837 not less than 3,921,259 bushels of wheat were imported into the United States."

Crop yields in eastern States. During those depressing years of land abandonment, crop yields were very low. The farmers of Sandy Springs, Md., on brown forest loams (*Chester* series), reported yields as low as 8 or 10 bushels of wheat, from 10 to 20 bushels of Indian corn, half a ton of hay, and from 30 to 60 bushels of potatoes to the acre; and there seemed to be no solution of the soil-exhaustion problem.[9]

Manure was scarce, due to the fact that tobacco and wheat farming, and cotton growing in the South, did not encourage the keeping of much livestock. Lime was used, but without much general success, until Ruffin (1832) demonstrated and taught that on acid and exhausted soils the addition of organic matter (manure, pine "shats," leaves, and green manure) must precede liming. Follow-

8 Document No. 74, p. 69. Feb. 8, 1842.
9 Unpublished minutes of Farmers' Club of Sandy Springs, Md.

ing this demonstration and teaching, the burning of lime for soil improvement became a common practice.

The turning point. The year 1840 marks the turning point of agriculture in the eastern States. Bone "dust" (crushed bones) appeared as a fertilizer in 1839, and in 1844 Peruvian guano came on the market. The latter product became so popular that it was called the "King of Fertilizers" and the "miracle fertilizer." A small shipment of nitrate of soda from South America arrived at the port of New York in 1830, but its use as a fertilizer was not successfully demonstrated. This material did not come into use until about 50 or more years afterward; on the decline of the original guano supplies, this nitrate came into favor, particularly on the cotton plantations of the South.

Progress in improvement. Following the use of lime, bone dust, and guano, and the adoption of improved English methods of farming, steady improvements were made, as may be shown by the following averages of crop yields recorded in unpublished minutes of the Farmers' Club of Sandy Springs, Md., which was organized in 1844:

AVERAGES OF THE CROP YIELDS PER ACRE REPORTED BY MARYLAND FARMERS
(Soil Type, *Chester loam*)

Period	Oats	Hay (mixed)	Wheat	Indian Corn	Potatoes
	Bushels	*Tons*	*Bushels*	*Bushels*	*Bushels*
Before improvement began.....	15.0	0.5	9.0	15.0	45.0
1844 to 1847 (incl.)...........	17.1	0.75	13.0	22.5	58.3
1854 to 1856 (incl.)...........	26.2	1.0	20.0	40.7	67.0
1875 to 1877 (incl.)...........	34.0	1.0	22.3	40.1	87.0
1888 to 1895 (incl.)...........	21.2	1.4	22.1	46.0	94.1
1915 to 1921 (incl.)...........	—	1.5	21.5	60.0	140.0

NOTE: Continued increase in yields of wheat was checked by weevils and blight; and oats proved to be uncertain and commonly unprofitable, because the climate was not favorable for this crop.

Regeneration of worn-out lands. The solution of the soil-exhaustion problem of the eastern States was found in the improved methods of agriculture made possible, after 1840, by scientific knowledge. Evidently Honorable Thomas G. Clemson (1859) recognized this fact when, in the United States Patent Office Report for that year, he wrote:

Let that nation beware, whose exhausted fields are forcing her population to emigrate. . . . There can be no civilization without population, no population without food, and no food without phosphoric acid. . . . We

are on the eve of a movement from the West back to the East, where a different work is in prospective, that of the regeneration of worn-out land.

From predatory to permanent agriculture. As the United States developed westward, agriculture in the eastern settled sections gradually passed from the predatory stage to more permanent

Fig. 37. Extensive agriculture. Wheat farming in northwest United States. Upper—Three disk harrows, a grain drill, and corrugated roller at work. Lower—Harvesting with a 32-horse-team combine.

types. In most sections of the country pioneer methods of farming have disappeared. The farmers of the Middle West, who formerly believed that their soils were inexhaustible, in time experienced declining yields. Some communities have had to contend with the same problems that other pioneers had experienced in predatory cultivation and in its transition to more enduring agriculture. Fortunately, the pioneers found in America wide expanses of productive, virgin soils. The wealth that the earth yielded through the natural productive power of these soils made possible the firm building of the Nation's foundation (Figs. 37 and 38).

Causes of soil exhaustion. The principal direct causes of soil exhaustion concern plant nutrition. Crops may fail because of the inability of soils to supply the necessary nutrients. This inability commonly results from the removal of the supply of available nutrient elements by cropping and leaching. An exhausted soil may represent several unfavorable conditions that may have developed from continual cropping. Many soils become unproductive

Fig. 38. Intensive agriculture. Lettuce and strawberries with overhead irrigation.

upon the removal of organic matter or carbonate of lime, or both. Commonly, the problem of soil exhaustion is a complex one—so many factors must be taken into account to determine the necessary steps for improvement. Improvement or regeneration of some soils may prove to be a slow and tedious process, if not altogether unprofitable.

Importance of major nutrients. The experience of farmers generally, since 1840, and the results of thousands of field experiments throughout the world have shown that nitrogen, phosphorus, potassium, and calcium are the major elements concerned in crop production, soil improvement, and fertilizer practices; and their unavailability or absence results in the development of a high degree of soil acidity or alkalinity and in soil exhaustion. The relation

of these facts to natural law may be stated as follows: All higher plants, although differing widely in outward form—such as wheat, cotton, potatoes, cabbages, and onions—may develop and grow to full maturity through the assimilation of the same kinds of essential elements.

Quantity of major nutrients removed. In the table on pages 184 and 185 are given the quantities of the major nutrient elements that are taken up in the production of some common crops. The data are based on yields commonly obtained on productive soils, and have been compiled from various sources. Where called for, the quantities are given for the principal parts of the harvested crops: that is, grain and straw, lint and seed, and grain and stalk. The data are given in terms of elements, which is the only basis for comparison.

The quantities of elements given in the table on pages 184 and 185 do not represent the totals that crops require during growth, but rather the quantities contained in harvested crops. Roots require considerable quantities, likewise vines, such as those of potatoes, and also wood and leaves, as in case of fruit trees. The mature vines of a 200-bushel potato crop contain about 18 pounds of nitrogen, about 1.5 pounds of phosphorus, 2 pounds of potassium, and about 15 pounds of calcium. The refuse leaves and stems of a 15-ton cabbage crop contain considerable nitrogen, potassium, and calcium. In the production of tree fruits, from 20 to 75 pounds of nitrogen, 2 to 10 pounds of phosphorus, 20 to 50 pounds of potassium, and from 25 to 80 pounds of calcium are required an acre for leaf growth and new wood. Furthermore, during maturity considerable quantities of potassium pass out of plants. The pounds of nitrogen for legumes are placed in parentheses, as much of this element may be supplied by soil air.

THE FOOD PROBLEM

The population of the world increased from 1,009 millions in 1845 to about 2,100 millions at the present time. If one considers seriously the problem of growth of the world population, he might well ask the question, Will there be room on the earth for all the people and can sufficient food be produced?

Malthusian theory of population. The problem of population in relation to food supply was brought into prominence in 1798 by Thomas R. Malthus, an English economist, as a result of his

discussions with his father regarding the perfectibility of society. What prompted Malthus to publish an essay entitled "The Principle of Population, as It Affects the Future Improvement of Society" (1798, 1803) was the low status of agriculture near the close of the eighteenth century, in its relation to population. Malthus held the view that the realization of a happy society will always be hindered by the miseries resulting from the tendency of population to increase at a faster rate than that of food production. In his essay he formulated for the first time the so-called "law of diminishing returns" as applied to agriculture, though he did not name it such (see Index).

Baker (1931) has pointed out the fact that during the eighteenth and nineteenth centuries the population of the world had increased twice as much as in all centuries preceding. Little wonder that Malthus viewed the future with forebodings.

The Malthusian theory influenced public opinion for about 50 years, when unexpected development of scientific agriculture, transportation, and power resources, which made possible increased production and the development of large-scale industrialism, upset Malthus' calculations. Another factor of great importance was the development of farming on the grasslands—the prairies and Great Plains of North America, the steppes of Russia, the pampas of South America, and semiarid lands of Australia. In America, prairie farming began about 1849.

In large areas in India and China the Malthusian "principle" seems to reign supreme, because of the overwhelming population, general ignorance of the people, and the almost complete absence of scientific agriculture. It is interesting to note that, following the World War, considerable interest developed regarding Malthusianism, probably owing to food shortage during the war. According to Pearl (1924), the population of the world is going to increase for a long time to come, but that does not necessarily mean that human misery will follow the same course. Human beings will add to their knowledge of natural forces and will learn to control and use them for benefit. Pearl has pointed out that one must not overlook "the wholly unknown and unplumbed adaptive potentialities of the human organism."

Crookes' review of nitrogen situation. In his famous presidential address to the British Association for the Advancement of Science, in 1898, Sir William Crookes reviewed the problem of

The Quantity of the Major Nutrient Elements Removed by Harvested Crops

Crop	Yields per Acre	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Calcium (Ca)
Field Crops					
		Pounds	*Pounds*	*Pounds*	*Pounds*
Alfalfa (hay)	4 tons	(190.0)	19.0	150.0	150.0
Barley, grain	40 bu.	35.0	7.0	8.5	1.0
straw	1 ton	12.0	2.0	23.0	7.5
Total		47	9	31.5	8.5
Bluegrass (Kentucky)	2 tons	53.0	9.5	70.0	12.0
Buckwheat, grain	30 bu.	22.0	5.5	7.5	0.5
straw	0.75 ton	12.5	1.0	14.0	10.5
Total		34.5	6.5	21.5	11.0
Cabbages (heads)	15 tons	105.0	9.5	72.0	36.0
Clover, red (hay, cut in bloom)	2 tons	(84.0)	10.0	51.0	85.0
Clover, alsike (hay)	2 tons	(82.0)	12.0	57.0	40.0
Clover, Japan or Lespedeza (hay)	2 tons	(78.0)	18.0	68.0	40.0
Corn, maize, grain	65 bu.	60.0	9.0	12.0	1.0
stalks (stover)	1.75 tons	33.0	7.0	40.0	12.4
cobs	900 lb.	3.0	0.5	4.0	0.1
Total		96.0	16.5	56.0	13.5
Corn, maize, for silage	12 tons	82.0	17.0	88.0	14.0
Cotton, lint	500 lb.	1.0	0.3	2.5	0.5
seeds	1,000 lb.	38.5	6.5	10.0	2.0
stalks and leaves	2,000 lb.	28.5	3.5	16.0	11.5
Total		68.0	10.3	28.5	14.0
Cowpeas (hay, cut in early pod)	2 tons	(124)	14.0	135.0	36.0
Flax, grain	15 bu.	30.5	5.5	6.8	2.0
straw	0.9 ton	20.5	1.5	15.7	9.5
Total		51.0	7.0	22.5	11.5
Hemp (dry stalks)	3 tons	20.0	4.0	44.0	30.0
Mangels, roots	20 tons	90.0	14.5	165.0	14.5
leaves (green)	8 tons	46.0	6.5	58.0	25.0
Total		136.0	21.0	223.0	39.5
Millet (hay)	3 tons	80.0	9.5	107	16.5
Oats, grain	50 bu.	35.0	6.0	7.5	2.0
straw	1.25 tons	15.0	2.5	35.5	8.0
Total		50.0	8.5	43.0	10.0

Onions, bulbs only	500 bu.	60.0	11.0	52.0	31.0
Peas (canning) grain	20 bu.	44.0	4.5	10.0	2.0
straw	1.5 tons	30.0	2.5	26.5	42.5
Total		(74.0)	7.0	36.5	44.5
Potatoes (Irish), tubers	200 bu.	45.0	8.5	60.0	3.5
Rye, grain	25 bu.	26.5	4.5	6.6	0.5
straw	1.25 tons	12.0	3.0	16.4	5.5
Total		38.5	7.5	23.0	6.0
Soybeans, grain	20 bu.	70.0	7.0	24.5	2.2
straw	1 ton	35.0	5.5	32.5	31.3
Total		(105.0)	12.5	57.0	33.5
Sugar beets, roots	15 tons	78.0	10.5	80.0	8.0
leaves (green)	6.2 tons	40.0	6.5	12.5	30.5
Total		118.0	17.0	92.5	38.5
Sweetpotatoes, tubers only	200 bu.	35.0	5.0	51.0	—
Timothy (hay)	2 tons	40.0	5.5	4.5	10.0
Tobacco, leaves	1,500 lb.	41.0	3.0	60.0	41.0
stalks	1,250 lb.	26.0	2.5	33.0	7.0
Total		67.0	5.5	93.0	48.0
Turnips, roots	15 tons	60.0	12.0	72.0	24.0
leaves (green)	5 tons	43.0	4.0	28.5	42.5
Total		103.0	16.0	100.5	66.5
Wheat, grain	30 bu.	35.5	6.5	7.5	1.0
straw	1.6 tons	16.0	2.5	16.5	6.5
Total		51.5	9.0	24.0	7.5

Fruits

Apples, fruit only (50 to 75 trees an acre)	100 bbl.	14.0	2.0	15.0	1.0
Cherries, fruit (108 to 120 trees an acre)	150 bu.	16.0	2.6	16.5	1.0
Peaches, fruit (100 trees an acre)	450 bu.	19.5	4.2	32.5	2.0
Pears, fruit (75 to 90 trees an acre)	500 bu.	10.5	1.6	19.2	2.0
Plums, fruit (90 to 100 trees an acre)	250 bu.	22.0	3.6	25.5	2.0
Raspberries (fruit only)	3,000 qt.	10.0	2.0	10.0	—
Strawberries (fruit only)	6,000 qt.	13.5	4.5	22.5	1.0

feeding the increasing population of the world, devoting his attention particularly to wheat, the staple food of the white race. He concluded that by 1931 all the available wheat lands of the world would be required to produce sufficient wheat to feed the population; and after that, owing to exhaustion of the supply of natural nitrates, the world would begin to feel the pinch of hunger.

Crookes' object was to direct the attention of scientific men to the necessity of finding some means of fixing atmospheric nitrogen

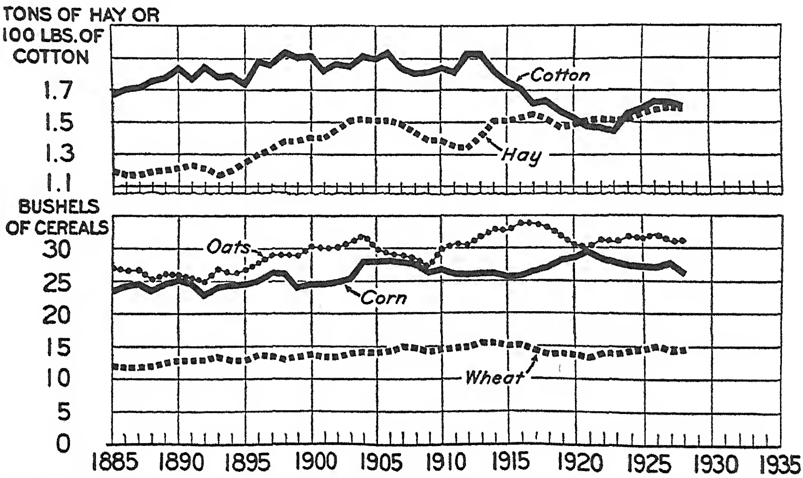

Fig. 39. Trends of crop yields in the United States since 1885, based on 5-year moving averages. It is to be noted that the acre yields of wheat are now slightly higher than at the beginning of the century, despite the expansion of production into semiarid regions.

so as to provide an adequate future supply of bread. He suggested harnessing Niagara Falls in order to obtain adequate quantities of usable nitrogen for the reinvigoration of exhausted soils.

Here attention should be called to the discovery that Cavendish (Eng.) had made as early as 1785. He found that nitrogen and oxygen united when electric sparks were passed through a mixture of the two gases. This discovery was not put to practical use for 118 years, until 1902. Crookes, however, saw the significance of this discovery.

Modern agricultural science and invention have more than met those seemingly insuperable dangers that beset humanity, pointed out by Crookes. Within less than 10 years his dream of the commercial production of fixed nitrogen from the air was real-

ized in the electric-arc and calcium-cyanamide processes (respectively, 1902, 1905); and soon after in the direct synthetic-ammonia process which was made commercially successful in 1913.

General trends of crop yields. The general trends of crop yields of Europe and America since 1840 have been upward. The improvement has resulted from several factors, including use of commercial fertilizers, the use of feeding stuffs for livestock, better

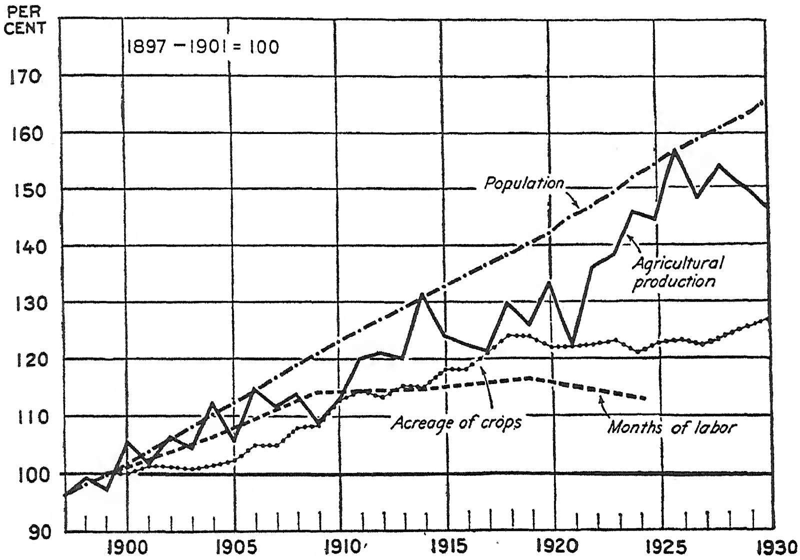

Fig. 40. Agricultural production in the United States. Although production is now about 50 percent greater than at the beginning of the century, crop acreage is only 25 percent greater, and the quantity of labor employed in agriculture is only about 12 percent greater.

tillage, rotation of crops, better seeds, and improved varieties. In the older agricultural sections of the United States, as in the eastern States, the general upward trend during recent years has been greater than in some other sections. Figure 39 shows the upward curves of the yields of cotton, hay, oats, Indian corn, and wheat in the United States since the beginning of the present century.

Baker (1931) has shown that, although agricultural production in the United States is now about 50 percent greater than at the beginning of the twentieth century, acreage of crops is only 25 percent greater, and quantity of labor employed in agriculture is only about 12 percent greater (Fig. 40); so that production per

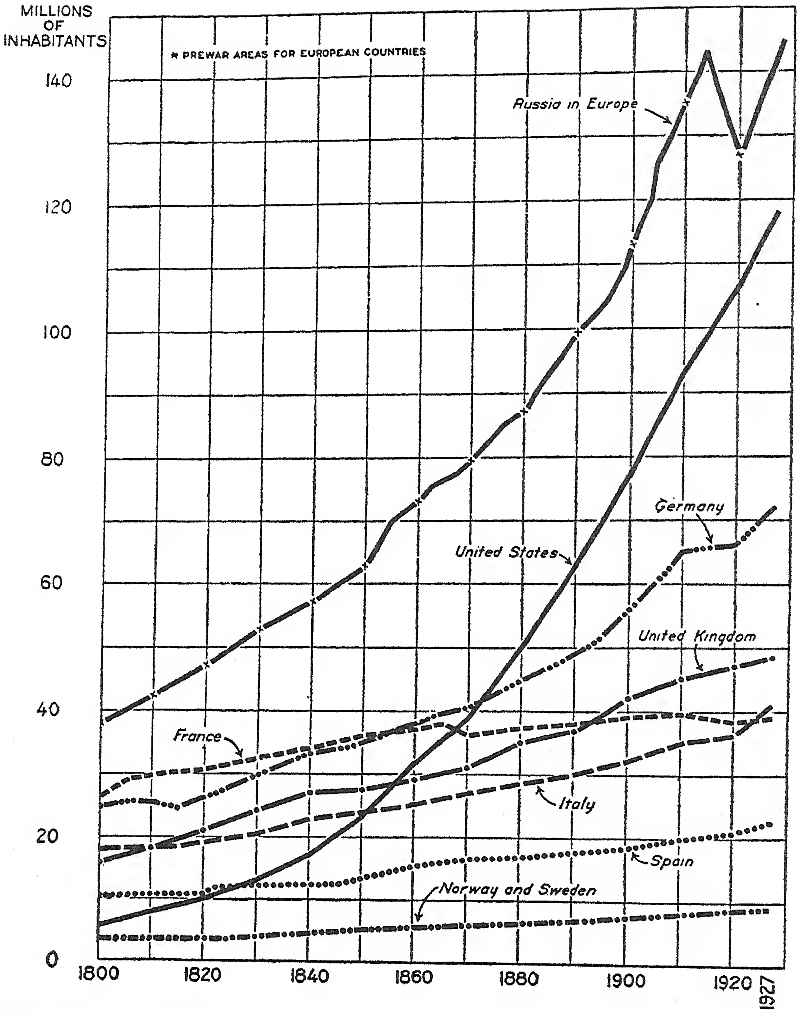

Fig. 41. Population of the United States and of the principal countries of Europe.

acre has increased about 20 percent, and production per man about 34 percent. It is to be noted that most of this increase has occurred since the World War.

Future outlook regarding food. The best judgment of population statisticians is that before the close of the twentieth century the United States will have a stationary population of between 150 million and 170 million people. Figure 41 shows graphically the

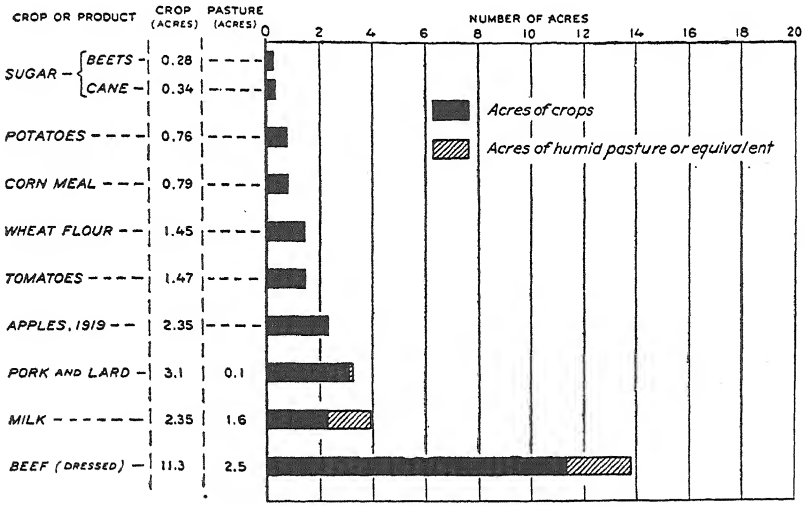

Fig. 42. Comparative importance of crops and livestock, based on acres required to produce 1,400,000 calories of food energy. (The yearly consumption of food per person averages 1,400,000 calories.) To maintain health, meat, milk, carbohydrates, and other foods high in protein fat are required.

population of the United States and of the principal countries of Europe. In summarizing the outlook regarding the food problem of the United States, Baker (1931) has concluded that the prospect is for an increase of 12 or 15 percent in consumption 10 years hence, 20 or 25 percent increase 20 years hence, and about 30 percent increase 30 years hence, when it will become practically stationary for a few years; then it may decline.

The land area required to meet domestic consumption will vary also, with changes in crop yields and relative importance of crops and livestock, and with other factors (Fig. 42).

From the world point of view, the food resources at the present time are ample, as a result of a more efficient agriculture, improved

transportation and distribution, reduction of wastes, and increased efficiency in finance and commerce. Dublin (1932) held the opinion that the crux of the food problem is not the absolute number of people, but rather the relation of the numbers of people to the necessities available to them through our existing channels of commerce.

Owing to the fact that there are no more great stretches of unoccupied fertile lands in temperate regions, like those that were settled during the nineteenth century and that provided ample food for the unprecedented growth of world population, it seems evident that agricultural production adequate for the future needs of the world population cannot be effected by extending the areas of cultivated lands, but rather through intensification of farming on lands now occupied and through development of tropical sources of carbohydrates, fats, and proteins. With the advance in agricultural sciences and the marvelous improvements of machinery for tilling the lands and for harvesting the crops, it is unlikely that the food supply of the world will ever again be menaced in the absence of plagues, climatic disturbances, land destruction, and war.

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REVIEW QUESTIONS

1. Sketch the development of the present concept regarding the sources of plant nutrients.
2. Explain the changes in the requirements of a green plant from seed to maturity.
3. Discuss the intake of carbon dioxide and nitrogen in relation to photosynthesis.
4. What distinction has been made between the major plant nutrient elements and the trace-essential elements?
5. What is the function of each of the essential nutrient elements, so far as plant growth is concerned?
6. What distinction may be made between a nutrient element and a plant food? Explain and give examples.
7. As regards plant nutrition, what is the significance of the close contact that plant roots make with soil materials?
8. Discuss the principle of crop adaptation.
9. Is soil exhaustion a theory or a fact? Give evidence.
10. Discuss the Malthusian theory in the light of present world conditions (consult Index).
11. What important significance did Cavendish overlook regarding a discovery he made in 1785?
12. Discuss soil productivity in relation to the world food problem.
13. What is meant by the statement commonly made that coal is canned heat?
14. In what respects is the carbon cycle similar to the nitrogen cycle?
15. Point out on a map the areas of the major types of farming in the United States.

CHAPTER 10

CROP PRODUCTION AND SOIL FERTILITY

Through ancient times and well into the modern period the idea was strongly impressed upon human thought that soils were cultivated for food and little else. This idea is common even today. In the course of time, however, soils have been put to wider and wider uses. In addition to producing food crops, they support plants that yield lumber, vegetable fibers and oils, gums, beverages, stimulants, tanning materials, dyestuffs, and many medicines. They produce raw materials that have given rise to hundreds of industries. Cotton, for example, contributes to the manufacture of a great many articles of commerce, including cloth, clothing, airplane fabric, fabric for motor-car tires, explosives, celluloid, artificial silk, oils, paper, fuel, meal for livestock, and materials for fertilizers. Many products are also derived from maize, including foods, corn starch, alcohol, corn sirup, oil, feed for livestock, and paper.

The greater use of soils has been an important factor in making it possible for the human race to thrive in regions quite unsuited to primitive people. In fact, productive soils constitute the most important resource of a state or nation. Human progress is determined in a large measure by an abundance of food, and it is conceded that agriculture has been an important factor in the development of civilizations. Hence the importance of a system of productive and "permanent" agriculture. It probably will never be possible to dispense with the use of soils as the source of food, fiber, and other raw materials, and human society will probably be just as dependent on them in the future as at the present time.

Producing power of farms. A permanent and productive system of agriculture can be established in a country only as individual farmers and land owners give careful thought to soil conservation and to those factors that determine soil productivity. From his point of view, the practical problems of each farmer may be stated as follows: What can I do with the land under my

control? How can I preserve its fertility, and prevent its destruction? How can I use it profitably? What is the best system of soil management to follow?

On a given farm these problems may be solved from time to time by the individual farmer. The solution of these problems for any long period can be determined only through the practical application on a wide scale of the principles of soil productivity.

Farmers should not be solely concerned with the maintenance of the original fertility of soils, nor with the task of maintaining a high state of potential productivity. There is no scientific evidence to justify such a program. Moreover, such soil-management prac-

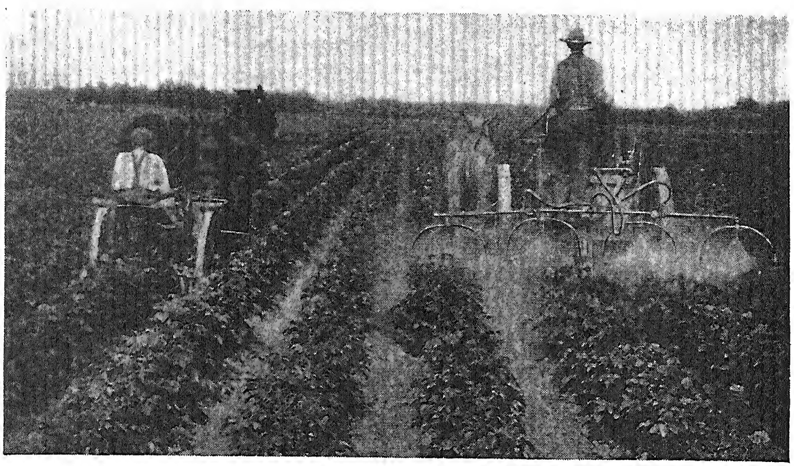

Fig. 43. A field of potatoes in New Jersey. In addition to fertile soil, good seed, favorable temperature, and sunlight, protection from diseases and insect pests is also an important factor in successful crop production.

tices would lead to enormous losses of valuable plant-food elements through leaching, principally. Successful modern farmers endeavor to have their soils meet the current needs of crops in accordance with scientific and economic principles.

Factors in crop production. Most of the principal factors that determine successful crop production—fertile soil, good seed, favorable temperature, sunlight, and protection of crops from injury—are not much different from those that were recognized by primitive husbandmen 10,000 years ago (Fig. 43). They soon learned what kind of ground was good for planting, that no plants grew

from bad seeds, and that warmth was necessary for plant growth. They experienced the favorable effects of sunshine on growing crops, and no doubt they learned very early that there would be no harvest without crop protection. In modern farming, however, improved seeds, varieties, and cultural methods have become potent factors in economic crop production.

Fertile soils. The production of abundant crops is determined largely by fertile soils. A soil is designated as fertile when crop

Fig. 44. Harvesting wheat on a Pennsylvania farm. Crop growth and yields may indicate soil fertility or infertility. (Pennsylvania Farms, Philadelphia.)

growth and yield indicate that it is productive (Fig. 44). The term "fertile" implies soil conditions and qualities that favor normal plant growth and development, hence good yields.

Some soils are naturally fertile, whereas others are not. Soils naturally unproductive may be made highly productive by correcting unfavorable conditions or qualities, or both. A wet peat soil, for example, may be made productive for Indian corn by proper drainage and the addition of suitable fertilizer, such as potash or phosphate, or both.

Relative meaning of "fertile." The terms "fertile" and "productive" and *fertility* and *productivity,* when applied to certain soils, have relative meanings, especially with reference to crops (or plant growth) and soil conditions. A soil may be fertile for one crop

and not for another. A rich black loam may prove to be very fertile in Texas for cotton, but a similar soil in Canada would be infertile for the same crop. Thus soil fertility may depend on climate. Again, an acid soil that may be very fertile for upland blueberries would be infertile for sweetclover which cannot stand acidity. In the latter case fertility depends on both the chemical nature of the soil and plant requirements.

Factors that determine fertile soils. Soil productivity is the conjunct effect of several favorable factors, including good tilth, sufficient water, aëration, soil reaction, organic matter, helpful soil micro-organisms, available nutrient elements, and crop rotation. The effect of any one of these factors, or even the combined effect of all, may be nullified by harmful agents that may be present, such as weeds, too much salt in the soils, plant-disease organisms, too much or too little water, harmful insects, and plant poisons.

The principal fertility factors are fully discussed in subsequent chapters. However, a few words may be said here regarding the other factors on which successful crop production depends.

Good seed. The value of good seed has long been recognized. It may be inferred that primitive husbandmen gave considerable attention to the selection of seed, which resulted in the early development of the cereal crops. Even before the Christian Era the Romans recognized good seed as an important factor in husbandry. Good seed does not imply high germination test only, but also selection according to standard variety, size, adaptation of variety, purity, resistance to disease, hardiness, high-yielding variety, and superior quality of produce.

Favorable temperature. The reason why warmth is an important factor in cropping has been explained in Chapter 9. Crop plants differ in their temperature requirements, as is shown in the widely different crops that are grown in the different climatic regions of the earth.

Light. The importance of light to green plants, as explained in Chapter 9, lies in the fact that sunlight is the source of energy in carbohydrate and protein synthesis. Under field conditions duration of light is more important than intensity. Some plants like those which manufacture considerable starch and sugar require more light than others. "Shade" plants usually have thinner leaves with less chlorophyll than "light" plants, to enable them to utilize to greatest advantage the light that breaks through the

leaves of the "sun" plants. This is illustrated by the cultivation of asparagus, cauliflower, celery, lettuce, and radishes which are best grown under half-shade, as this increases their tenderness and delicacy. Indian corn requires much sunlight.

Those who have had experience in making lawns know the importance of so-called "shade grasses" for shady places. Rough bluegrass (*Poa trivialis*) is especially well adapted for planting ground shaded by buildings, and European red fescue or Chewings fescue may be used under trees, especially when the soils are sandy and when other grasses fail. No grass can endure very long, however, under continuous heavy shade.

Shade for killing weeds. Shade is a most effective means for killing young weeds. Hence the use of so-called "smothering crops" which include fast-growing plants that quickly rise above the weeds and spread their leaves over them. As the result, the weeds die of starvation. The deprivation of sunlight is the important factor in killing young weeds by covering them with soil material through cultivation.

Thrifty crops like alfalfa and clovers may prove to be very effective for smothering weeds, which mainly accounts for prime alfalfa and clover sods being comparatively free from weeds. Hemp is another good weed-killing crop. Fast-growing weeds, on the other hand, may, if allowed to get ahead of crop plants, cause starvation of young alfalfa, clover, potatoes, and even small grains by shutting out the sunlight.

One crop may shade another. Too thick planting, thrifty growth, and lodging of small grains commonly smother out seedlings of grass and clover, mainly as the result of the exclusion of sunlight. In sowing small grains, there is an advantage to be gained in drilling the crops, as compared with broadcasting. Some farmers cross-drill when they plant both grass and small grain on the same ground. They drill in the grain in a direction that will allow the most sunlight to penetrate to the ground after the grain grows high above the grass.

Climate, weather, and crops. Russell (Eng., 1924) [1] has pointed out that in crop production, agricultural investigators are confronted with three important and closely interlocking factors—plant, soil, and climate—and that each of these factors is variable within certain limits.

[1] Russell, E. J. Report of the British Association for the Advancement of Science, Toronto, Canada, p. 260. 1924.

A plant is a very plastic organism which can be modified considerably by selection and breeding. As a result of research in plant breeding, plant varieties have been developed that can be grown under soil and climatic conditions that formerly had caused crop failure.

Soils are not fixed and constant bodies, but are pulsating with change. Neither are plant-soil relations fixed. They, too, are capable of considerable variations, being profoundly influenced by the third factor, which is climate or weather. Weather may have a much greater effect on crop yields than have fertilizers.

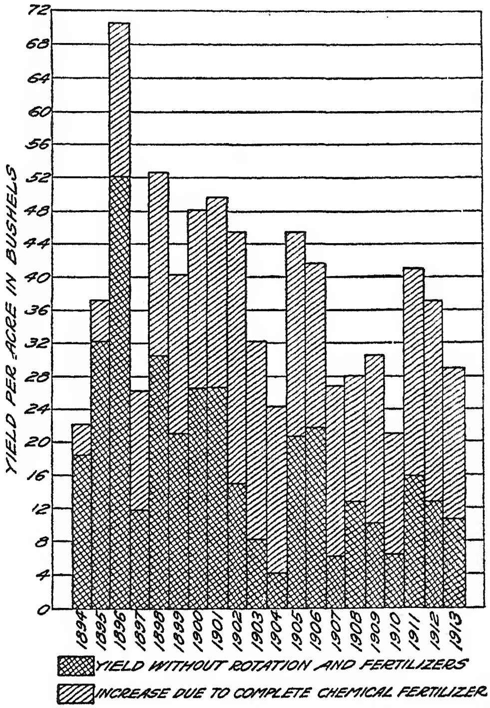

Fig. 45. Effects of weather on the yields of maize and on effectiveness of chemical fertilizers. (Continual-culture plots. Wooster, Ohio.)

In discussing the effect of weather on Ohio wheat, Bear (1923) has observed that October, January, March, and June are the critical months. A dry October, a warm dry January, a cold wet March, and a wet June seem to favor high yields. He has pointed out, also, that fertilizers may, within certain limits, counteract effects that adverse weather might produce.

The relation between crop yield and weather and between the effects of fertilizers and weather are illustrated in Figure 45, in which are graphically shown the average yields of Indian corn on fertilized plots numbered 2 and 3 in the continual-culture series at Wooster, Ohio.

Hall (Eng.)[2] has observed that the Dunbar potatoes, grown in

2 HALL, A. D. A Pilgrimage of British Farming, p. 133.

East Lothian, Scotland, possess qualities not to be equaled anywhere. He has concluded that the superiority of these potatoes seemed to be the result of an adjustment of the crop and soils to climate. Delwiche and Tottingham (1930) found an 11-percent higher protein content in red clover grown in southern Wisconsin than in the same kind of clover grown near Lake Superior.

SOIL FERTILITY

There seems to be considerable confusion in the use of the terms "fertile" and "fertility," and many persons believe that fertility may be actually leached out of a soil. The only difference in the words themselves is that one is the adjective form and the other (fertility) is a noun. As a matter of fact, fertility cannot be leached from a soil, because it is not a part of the soil itself, but rather only a quality. When the fertility of a soil is greatly diminished through leaching, it is the removal of the nutrient elements, principally, that changes the character of the soil from fertile to infertile. Thus *fertility* and *infertility* are both relative terms, inasmuch as they imply certain relationships between soils and crop yields—that is, they imply the ability and inability of soils to produce good yields of adaptable crops.

The terms "fertile" and "fertility" suggest the concepts of "infertile" and "infertility." Thus the term "fertility" implies a certain degree of productivity below which this term cannot be logically applied. Low fertility may mean rather low producing power, as indicated by rather poor crops or yields. Infertility means very low producing power. A sterile or barren soil illustrates the lowest degree of soil infertility.

The expression "fertility of a soil" has meaning only in the relation of a given soil to those crops that may be grown upon it. A yield of 50 bushels of corn (maize) an acre may indicate a fair degree of fertility of an acid silt loam, but an alfalfa failure on the same land may indicate infertility, so far as alfalfa is concerned. Such a soil, however, may be made productive for alfalfa by the addition of both lime and the proper kind of nodule-forming organisms.

Factors that determine fertility. Obviously, soil fertility is determined by the same interdependent factors that determine fertile soils, namely, good tilth, sufficient water, soil aëration, favorable soil reaction, soil organic matter, helpful soil micro-organisms,

available nutrient elements, and proper rotation of crops. The interdependence of these factors may be easily demonstrated.

A soil may produce low yields of Indian corn for the want of available phosphorus; but this does not mean that corn yields can be increased in proportion to all increments of soluble phosphate that might be applied. Increases may be effected up to a certain point, when yields may be limited by some other element, such as nitrogen, which may have become relatively deficient. Addition of nitrogen fertilizer may result in further increase up to a higher point, when water, perhaps, might become the limiting factor.

Nearly 1,941 pounds of lint cotton (Ariz., 1934), 1,000 bushels of potatoes, and nearly 255 bushels of corn (maize) (N.C., 1889) an acre are some outstanding yields that have been obtained, indicating that in each instance all the fertility factors must have been highly and, under favorable conditions, mutually effective (Fig. 44).

Interdependence of factors illustrated. Interdependence of the fertility factors is illustrated in Figure 46, in which the reservoir represents a well-drained peat soil, and the quantity of water held represents the yield of Indian corn. The reservoir, which is built partly of "planks," can hold no more water than the shortest plank will allow. If this short plank were lengthened, the water capacity of the reservoir would be limited by the next shortest plank, and so on.

The peat soil represented in Figure 46 is deficient in available potassium, as most peat soils are; the yield of maize might, therefore, be increased by the addition of potash fertilizer. Phosphorus would then become the next limiting factor, as is true in many peat soils. On meeting the second deficiency, further increase in yield might be limited by a sparse population of nitrifying organisms.

Soil exhaustion and fertility. Not much significance was attached to the idea of soil exhaustion until 1840, when Liebig declared that the function of fertilizing materials was to restore to soils the ash, or mineral, constituents removed by crops, and he applied the so-called law of "diminishing returns" and the "law of the minimum" to plant nutrition (Ch. 1). His statement of the law of the minimum, as applied to plant nutrition, has had a profound effect on agricultural thought. Liebig attributed the decay of Rome to soil exhaustion.

For many years following 1840, agricultural thought centered

mainly on the chemical elements concerned in plant nutrition. Soil exhaustion was interpreted in terms of the removal of the nutrient elements; hence, soil fertility came to mean an abundance of chemical nutrient materials. As knowledge of soils developed, however, the problems of fertility and exhaustion became more and

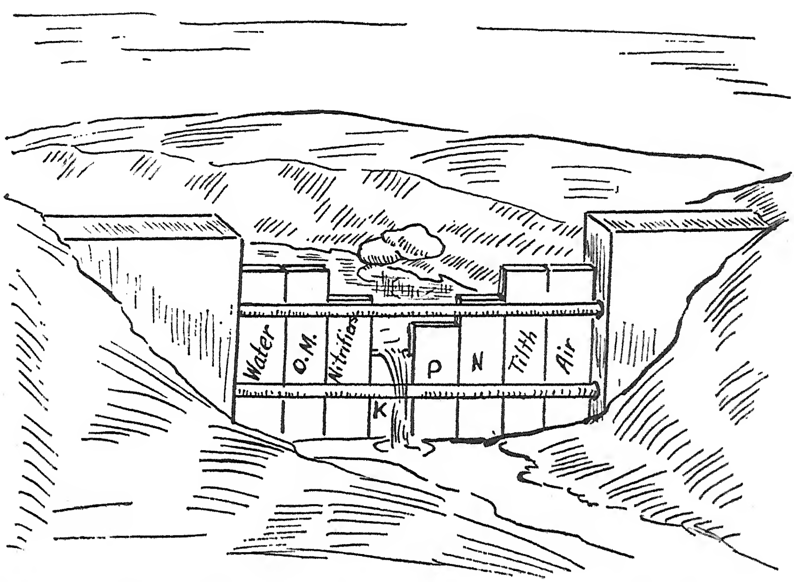

Fig. 46. Soil-fertility factors are interdependent. As the reservoir will hold no more water than the shortest "plank" will allow, so soil fertility may be limited by a deficiency of one nutrient element or by an unfavorable soil condition.

more complex, involving not only the chemical nature of soils but their physical and biological aspects as well.

SOIL DETERIORATION AND IMPROVEMENT

In relation to crop production, decline in yields may be caused by cropping, leaching, injurious insects and plant diseases in soils, poor cultural methods, and soil erosion. Cropping and leaching, disappearance of organic matter, and excessive soil erosion, may be regarded as the common causes of soil deterioration.

Cropping. Decline in yields is most rapid during the first few years following the breaking of virgin, fertile lands. Shutt (Can., 1925) found that of the total loss of soil nitrogen following the breaking and cropping of a virgin prairie soil, only one third

could be charged to the crops grown on it. The loss of nitrogen, above that used by the crops, averaged 75 pounds per acre annually for a period of 22 years.

According to Lawes (Eng., 1881), during the early stages of agricultural development in England only the more fertile soils were cultivated, and little or none of the produce was returned to the land as manure. Lawes stated that decline in yields was inevitable, and that these conditions gave rise to the practice of having long periods of rest between one series of crops and another. With the development of livestock farming and better soil-management methods, however, knowledge developed regarding not only the maintenance of soil productivity, but also the restoration of fertility.

On soils of either virgin or acquired productiveness, continual exhaustive cropping usually results first in a definite decline in fertility, and ultimately in low and rather stationary yields. This has been demonstrated by the yields of the "check" or untreated plots in many long-continued field experiments.

Soil deterioration by leaching. Bizzell (1926) gave a summary of all research data on removal of plant nutrients by drainage waters, as follows:

1. Calcium is the principal soil constituent that is removed by leaching, generally amounting to more than all the other nutrients together. Cropping tends to reduce the loss of this element by leaching, and acid-forming fertilizers increase the loss.
2. The quantities of magnesium and potassium removed by drainage waters are appreciable, but not excessive.
3. Nitrogen is leached from soils in the form of nitrates. Inasmuch as soils do not possess the power to retain nitrogen as they do potassium and phosphorus, for example, this element is easily lost from soils through leaching. Cropping generally reduces the quantity lost in this manner.
4. The quantity of phosphorus lost by drainage is practically negligible.
5. Comparatively large quantities of sulphur may be found in drainage waters. As with other elements, cropping lessens the loss of this element by leaching.

Removal of organic matter. Rapid decay of organic matter follows the breaking of virgin and sod lands. This decomposition of organic matter, mainly by fungi and bacteria, results in the liberation of most of the nitrogen, carbon, and mineral elements contained therein.

The first organic compounds to suffer loss are the energy-

producing materials, namely, carbohydrates and protein compounds. In subsequent cultivation, the rate of loss of organic matter or humus is determined by resistance to decomposition, until ultimately, if fresh plant residues are not added, only the most resistant substances remain. In many soils the organic matter has been reduced to very small percentages (Ch. 2).

In the destruction of soil organic matter, the carbon-nitrogen ratio is narrowed considerably, from as high as 40 to 1 and 20 to 1 in the original plant residues to 10 or 12 to 1 in ordinary agricultural soils. Exhaustive cropping narrows the ratio still more.

Soil erosion. The two agents that cause soil erosion are running water and wind. In this form of soil deterioration, the soil material itself is washed or carried away. Soil erosion is least active on level land, and has been kept under control for centuries on lands protected by vegetation (Ch. 6). On some gentle cultivated slopes, the rate of loss through accelerated run-off may be about 1 foot of the land surface in 300 years, whereas in other places 1 foot may be removed in about 25,000 years. Deterioration and destruction of the native, or natural, vegetation greatly increases soil erosion, and the cultivation of land, which usually follows the destruction of the natural protective vegetable cover, may bring about the same result. The problem of soil erosion is discussed more fully in Chapter 25.

General soil improvement. Weitz (1926) has analyzed the crop statistics of different countries in relation to soil fertility. He found that governments did not begin to gather crop-yield statistics until long after most virgin lands had been brought under cultivation, so that there are no official data available to show what the first average yields were. The available data, however, show trends toward more effective crop production, as are shown in Figures 39 and 40.

In a given country or region the trend in yield per acre over a long period represents the resultant of two groups of factors that work in opposite directions. One group tends to raise the yields and the other tends to depress them. There seems to be a gradual ascendancy in yields resulting from the first group of factors.

SOIL-FERTILITY INQUIRY

The fertility of a soil is determined by several interdependent physical, chemical, and biological factors whose combined effects

are expressed in the ability of that soil to meet the specific needs of crop plants. Requirements of crops may differ widely, as is indicated by alfalfa (lime-loving plants) and blueberries (lime-avoiding plants). The degree to which crop plants can obtain their needs is determined by the mediums in which they grow. The mediums, according to the modern concept, are earthy bodies which are designated and classed as soil types.

In pure soil science, typical virgin soils constitute the true basis for investigational work. But do typical soils also constitute the scientific basis for inquiry into soil fertility? Let us look into this problem. First we find that, locally, some definite relationships between soil types and yield and quality of produce have been found, as shown in the following discussion.

Soil types and crop yields. Weir (1926) has made a study of five principal types of soils of north-central Indiana in their relation to crop production, with the results shown in the following table.[3]

SOIL TYPES IN RELATION TO CROP YIELDS

Soil Type	Character of Soils	Number of Observations	Average Yields per Acre: Hay (Clover and Timothy)	Winter Wheat	Oats	Indian Corn
			Tons	Bu.	Bu.	Bu.
Crosby loam (Gray forest soils)	Gray silt loams with compact, light yellowish-brown silty-clay subsoils. Originally oak land, and not well drained.	60	1.0	15.5	28.5	30.2
Miami silt loam (Brown forest soils)	Yellowish-brown silt loams with yellowish-brown silty-clay subsoils. Originally "maple-walnut" land.	103	1.3	25.9	36.8	38.8
Carrington silt loam	Prairie soils with dark-brown topsoils and subsoils of yellowish-brown heavy-textured materials.	69	1.2	19.6	37.3	39.7
Brookston silt loam	Black silt loams with mottled yellowish or graying-yellow silty-clay subsoils. Represent medium conditions between upland and low wet areas.	85	1.7	21.1	43.2	48.9
Clyde silt loam	Black silt loams with bluish clay subsoils. Originally saturated with water.	64	1.8	22.2	44.5	52.6

3 Journal of the American Society of Agronomy, Vol. 18, No. 12. 1926.

The farmers gave special attention to the *Crosby* soils—drained them when necessary and added lime, organic matter, and manures. They recognized wide differences in these soils in their natural state (Fig. 15, Ch. 4). The *Clyde* soils were wet, and the *Crosby* soils were found to be so poor that they were called "graveyard" soils. Yet through special treatment, the *Clyde* soils, worthless when water-soaked, were converted into fertile fields; and some of the *Crosby* soils were made highly productive.

Stallings (1929) has reported wide differences in relative potato yields obtained on certain types of soils in Florida, as follows:[4]

RELATION OF TYPES OF SOILS TO POTATO YIELDS
(Florida)

Soil Type	Important Characteristics	Average Relative Spring Yield (1927 and 1928)	Average Relative Fall Yield
Norfolk fine sand	Open, lacking humus, and are droughty.	100	100
Leon fine sand (loamy phase)	Low moisture-retaining power.	130	140
Blanton fine sand	Low water-retaining power.	142	155
St. Johns loamy fine sand	Occur in low, poorly drained areas.	162	305
Portsmouth types	Contain most humus, are rather compact, and have moisture-retaining power.	189	321

Soil types and quality of produce. Elevator operators in north-central Indiana have long observed higher qualities in wheat grown on brown upland forest soils (*Miami silt loam*) than in wheat grown on prairie soils (*Carrington silt loam*). Greater weight per unit volume was one of the outstanding qualities of the forest-soil wheat.

The relationship of soil type to quality of bright tobacco is well known. In the production of burley tobacco, the Tennessee Agricultural Experiment Station found that soils that have developed from materials derived from high-grade limestone and Tellico sandstone produced higher yields and tobacco of better quality than soils that have developed from shale and slate materials. The

[4] *Soil Science,* Vol. 28, No. 2. 1929.

difference was expressed as acre returns of $403.92 and $368.28, respectively,[5] a difference of $35.64 an acre.

Fertility conditions may change and vary. Inasmuch as important natural soil conditions and qualities may change, the producing power of the soils of a type group may vary from infertility to very high fertility. Cropping, fertilizers, and agricultural lime may effect profound changes in soils. Chester loams, which are brown forest soils of eastern United States, afford excellent examples. Here production varies from alfalfa failure and very low yields of small grains and Indian corn, particularly in the southern part of this soil-type area, to yields of 4 tons of alfalfa hay per acre (total from three cuts), 45 bushels of wheat, 65 bushels of oats, and 100 bushels of corn, in southeastern Pennsylvania, the northern part of this soil area. Moreover, within a type group there may be a wide difference even in the natural fertility of a typical soil and a soil that may vary nearly 50 percent from typical; for example, typical fertile Miami silt loams, as compared with a Miami silt loam that borders a poor Crosby silt loam (see table on page 203).

Generally, it may be said that for most crops the state of a soil in regard to its natural or acquired productivity has a much greater effect on yield and quality of produce than have the characteristics that determine soil types. Principles regarding natural phenomena are discovered by virtue of constancy. Soil-type characteristics of oat soils, for example, may differ greatly, locally and generally; and the producing power of the individual soils of a type group may vary widely. Moreover, climate and weather affect crop yields and quality.

Under similar conditions regarding weather and crops, differences in yields and quality caused by characteristics that determine soil types are points that determine adaptation of specific crops to particular soils. Usually, however, these are local problems. Furthermore, investigators in pure soil science endeavor to obtain their basic facts principally from typical virgin soils. Most agricultural soils, however, are not typical, and all cultivated soils have been modified more or less through cropping and farm practices. Whether typical or not, all arable soils are mediums for crop plants. Moreover, in scientific classification, according to Wolf

5 Tenn. Agr. Expt. Sta. Circ. 33. 1930.

(Eng., 1929), attention is paid to the nature of the objects considered rather than to their human uses.[6]

Soil types v. land uses. In relation to land uses, the soil types in many an area present a very complex picture; whereas land suitability for crops presents a simple picture, and practical. However, certain soil characteristics may aid materially in determining proper soil-management practice. For example, some soils are strongly acid and others are deficient in organic matter. Soil acidity may call for agricultural lime, and deficiency of organic matter may suggest green-manuring or a cropping system in which grasses and legumes are given prominent places. But such problems are local and do not involve any soil-type principle. Soil science in its application should aim to simplify, not complicate. The large number of principal soil types in the Cotton Belt does not necessarily call for as many brands of fertilizers or ways of fertilizing cotton. However, in discussing soils in relation to fertility, management, and use of fertilizers, it may be very convenient to designate soils by scientific classes.

Basis for soil technology. The requirements of crops or plants of a given kind and of some varieties, which needs are practically constant, affords a much less diverse basis for soil technology or economic crop production than soil types. With this basis, the problems in soil-fertility inquiry should include the discovery of (a) the habits of economic plants or their physiological characteristics, (b) the factors of growth and development and how these factors operate, and (c) how the requirements of economic plants can best be met through soils, regardless of types, whether typical or not, whether rich or poor (see "In conclusion," p. 150).

Development of soil-fertility inquiry. Russell (Eng., 1924)[7] has pointed out three periods in the development of soil-fertility inquiry, as follows:

1. The first period of 80 years (1804-1884) was ushered in by the precise and scientific work of De Saussure (Switz.). (See Index.) The principal object of investigation during this first period was to find out how to supply plants with the nutrients they need. During this period, Boussingault (Fr., 1834) inaugurated scientific field experiments; Liebig (Ger., 1840) drew his inference that plants took in simple mineral and gaseous substances and out of them manufactured complex organic com-

[6] WOLF, A. SCIENTIFIC METHOD. Encyclopedia Britannica, Vol. 20, p. 129. 14th edition. 1929.

[7] Report of the British Association for the Advancement of Science, Toronto, Canada, p. 256. 1924.

pounds; and Lawes and Gilbert (Eng., 1843) established successful fertilizer practice.

2. During the second period, soil micro-organisms received special attention. Berthelot (Fr., 1885) was the first investigator to infer that an increase in soil nitrogen was caused by the activity of micro-organisms. During this second period Hellriegel and Wilfarth (Ger., 1888) proved the fixation of atmospheric nitrogen by symbiotic or nodule-forming bacteria; Winogradsky (Russ., 1890) isolated nitrifying organisms; and Winogradsky (1893) and Beijerinck (Ger., 1901) isolated nonsymbiotic nitrogen-fixing bacteria.

3. Russell named the year 1897 as the probable beginning of the third period, during which the purpose was not to feed the crops, but to study crop plants and to discover what factors determine growth, and how these factors operate. Research along these lines began almost simultaneously in the United States, France, and Germany.

The soil-fertility inquiry at Rothamsted is based not on soils but rather on crop plants.

Although, in modern soil-fertility inquiry, attention is becoming centered on crop plants, many soil factors are involved. This trend in soil-fertility research was plainly shown at the First International Congress of Soil Science in 1927, when soil scientists from the principal countries of the world met in the United States to discuss nutrition of crop plants, soil fertility, the physical, chemical, and biological aspects of soils, and soil classification. Furthermore, the membership of the International Society of Soil Science and the wide range of subjects discussed at the congresses of this scientific body clearly indicate a universal recognition of the fact that *soil science has come to mean systematized knowledge of soils and of their fertility.*

Principle of soil fertility. The problem of soil fertility has taken this form: To find out how to meet the needs of plants through soils in the best manner, as may be determined by plant requirements, farm economy, and the effects produced upon the soils and plants by the methods used.

This statement of the soil-productivity problem implies a principle of soil fertility which may be stated as follows: *Where other conditions are favorable, sustained or increased yields result when through the soils the needs of the plants are properly met.* Practical applications of this principle are given in Chapter 23.

It seems best, in continuing the discussion of soil fertility, to consider separately the factors that affect soil conditions favorably

or unfavorably for the growth and development of crop plants. These factors include *tilth, soil water, aëration, soil reaction, soil organic matter, soil micro-organisms, plant nutrient elements,* and *crop rotation.* These factors seem to be the logical ones on which to base a scientific discussion of soil fertility.

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REVIEW QUESTIONS

1. Discuss soils in relation to the development of industries and civilizations.
2. What may be regarded as the fundamental economical problem in soil productivity?
3. Discuss the meaning of *soil fertility*. What does this term suggest regarding the producing power of soils?
4. To what extent can one fertilize crops to overcome unfavorable weather?
5. Compare Liebig's views regarding soil exhaustion and improvement with the modern views.
6. What relationship may be found between soil types and crop yields? Explain why.
7. Discuss the merits of soil types and crop requirements as the bases for scientific study of soil fertility.
8. What relationship is there between the principal factors that determine soil fertility and crop requirements?
9. Discuss the relationship between scientific soil classification and land utilization.
10. How may the principle of soil fertility be stated? Explain why this is a principle. Would it be the statement of a principle if "specific types of soils" were substituted for "the soils," and "specific crops" for "the plants"? Explain.

CHAPTER 11

TILTH AND TILLAGE

Good tilth may be called the "primary soil-fertility factor" for several reasons: Preparation of the earth for the reception of seeds was certainly the first experience of neolithic husbandmen. And in modern farming, good tilth is universally recognized as fundamental in planting, for seed germination, root development, and for subsequent plant growth (Ch. 9). The development of good tilth is accomplished through the use of specially devised implements.

Objects of tillage. In tillage, besides the development of good tilth, the following objects may also be attained: Organic matter and fertilizing materials may be incorporated into the soils, "raw" subsoil material may be brought to the surface and subjected to weathering, weeds may be suppressed, and the ground surface loosened to aid in the trapping of precipitation water and in conserving soil water. One or more of these objectives may be attained in a single operation.

PREPARATION OF THE SEED BED

In farming operations, different types of implements are used to develop good tilth, including plows, pulverizing and consolidating implements, and tools for subsequent cultivation. Inasmuch as soils differ in their physical constitution and crop plants differ in their characteristics and requirements, the development of good tilth calls for different soil treatments.

Soil moisture and tillage. All soils till best when they are moist. The optimum water content for tilling is determined largely by soil texture. Working a heavy soil when it is too wet puddles it (Ch. 3), and causes the development of clods or hard lumps. This is one reason why heavy-textured soils require careful management (Fig. 47). Sandy soils, strongly silty soils, and well-sodded lands may be plowed when rather wet without any appreciable harm.

Sandy, loamy, and silty soil textures, and granular and crumby

soil structures, also organic matter or humus and, on acid clay soils, carbonate of lime favor the development of good tilth.

Plowing. Plowing is beneficial in many ways, but the primary object of plowing is to loosen the topsoil materials to form a seed bed. Plows do this by cutting and turning the surface layers of soils as furrow slices which may vary in thickness from a few to

Fig. 47. Condition of a heavy-textured soil after having been plowed too wet. When the natural structure of a clayey soil is destroyed by working the land when it is too wet, a puddled condition results, and hard lumps develop as the soil dries out.

8 or more inches, and in width from 9 to about 14 inches. The inversion of the furrow slices loosens the soil through the pulverizing action of the moldboard, exposes a large area of fresh soil material to the action of the weathering agents, covers surface trash or plant growth, and smothers weeds by turning them under.

Plows. Essentially, a plow consists of a frame or body to which are attached *handles* or levers for control, a *beam*, *share* for cutting the bottom of the furrow slice, *landside* for taking the side thrust, *moldboard* or breast for turning the furrow slice, and *colter* or jointer for cutting the furrow slice vertically on the land side. There may be attached also a wheel for gaging depth, and wheels for carrying the plow.

Three kinds of colters may be used: namely, *knife* colters (including hanging, fin, and knee blades) which may serve for general use, except for cutting very tough sod and turning under coarse litter; *rolling* or disk colters, for cutting tough sod and coarse surface material; and *skim* colter or jointer which is commonly used, when plowing grass sod or turf land, for cutting out

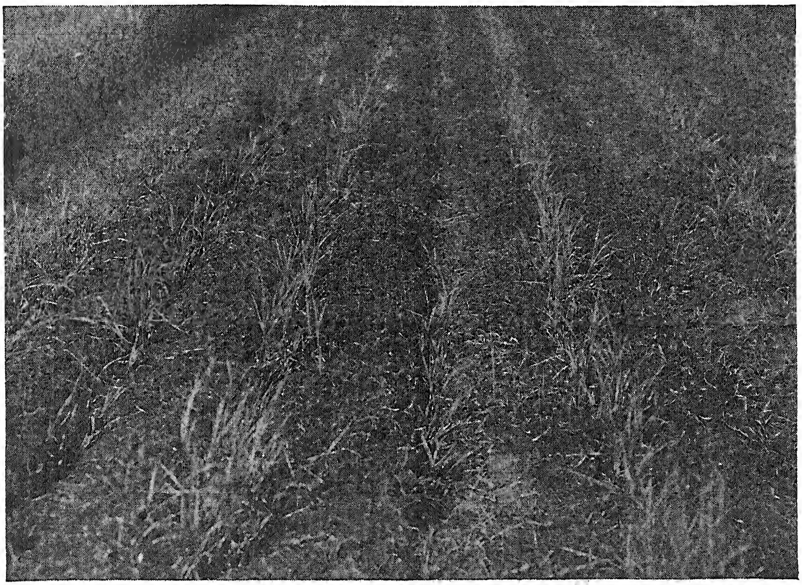

Fig. 48. Not a "clean" job of plowing old turf, owing to neglect in turning under all the grass. Plowing such land calls for the use of the right kind of jointer to turn under the grass.

a small strip of the turf on the land side and turning it into the furrow, thereby effecting a "clean" job of plowing (Fig. 48). Combined disk and skim colters are also used to assist in turning under heavy stubbles (Fig. 49).

Types of plows. On the basis of use, plows may be grouped into three classes, as follows: *breaker* plows with long sloping shares and moldboards of gentle curvature for raising and turning the furrow slices of sod or turf ground gradually without breaking them; *stubble* or digger plows with rather short, abrupt moldboards for breaking up the furrow slices of stubble and cultivated land; and *general-purpose* plows with intermediate moldboards, suitable for general use.

On the basis of construction, plows may be classed as *walking* or *riding,* according to whether the plowman walks or rides, and *disk* plows which have revolving disks instead of shares and moldboards (Figs. 50 and 54).

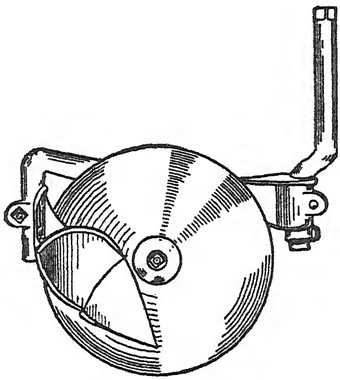

Fig. 49. Combined rolling and skim colter.

Some plows are constructed with two reversible moldboards to enable the operator to turn the furrow slices in one direction only, thus eliminating back-furrow ridges and dead furrows. Such implements are called "one-way," "double," "hill-side," "reversible," "turnwrest," and "swivel" plows.

Plows that turn a single furrow are commonly called "one-bottom" plows. Sulky plows (usually with three wheels) may have one or two bottoms. Implements that turn two or more furrows at a time are called "gang," "tractor," and "multiple-gang" plows. When large areas are to be plowed, and when conditions are favorable, 14-bottom, big-engine plows are often used, particularly on large level tracts.

Disk plows are particularly suitable for turning very hard

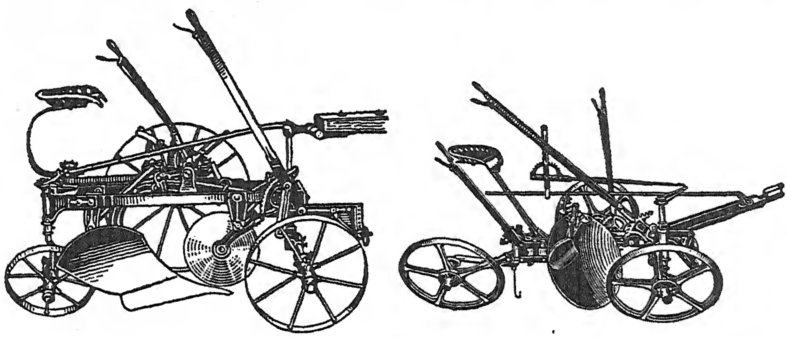

Fig. 50. Two types of riding plows: left, a sulky, one-bottom moldboard plow; right, a sulky disk plow.

ground like dry "adobe" soils, for plowing sticky or waxy land, and for loose muck and peat soils when moldboard plows will not operate.

Subsoil plows are designed for breaking up the soil material

below the furrow without bringing it to the surface. Such plows have steel tines rather than moldboards. Commonly, subsoiling is not advisable, except, possibly, in breaking up injurious hardpans.

After-harvest plowing. The time to plow may be determined by the planting season, moisture condition, farm-labor program, and special objectives. Many farmers plow at times when farm work is not pressing—immediately after harvest, in late fall, and in warm regions, during winter months. When the seed bed is to be deepened, fall plowing is usually best, as this allows settling of the soil material, thereby reëstablishing close contact between soil particles. Furthermore, if considerable "raw" subsoil material is brought to the surface, it may become sufficiently weathered before planting time.

Plowing or listing soon after harvest (with subsequent cultivation to kill weeds) has been found best for wheat, since this practice favors the accumulation of moisture and nitrates, particularly under conditions of limited rainfall. Wheat, with its system of fine, fibrous roots, requires a firm seed bed. In growing beets, fall plowing from 7 to 10 inches deep is a successful practice. On sandy soils, fall plowing is generally best for early spring cereal crops.

In farming under conditions of limited rainfall (dry farming), it is commonly advisable to plow immediately after harvest, not only because this is the best time to develop good tilth, but also because of favorable moisture conditions and for water conservation.

It is commonly advisable to plow highly productive soils that are intended for spring oats and barley in the fall, if they are plowed at all, to allow the seed bed to become compact before planting. Compactness of soil material will check nitrification and thereby prevent lodging which may result when such crops obtain too much nitrogen.

The following are other advantages that may be gained in fall plowing: It favors development of good tilth and granular and crummy soil structure, especially in heavy soils, and when there is frost action (see Index). Certain crop pests may be destroyed, such as grubworms, cutworms, and corn rootworms; and coarse litter turned under becomes partly decomposed and compressed, thereby establishing close contact between the seed bed and the subsoil. Furthermore, but little injury results to the physical

condition of heavy soils when they are plowed in the fall, as compared with too wet plowing in the spring.

Farmers in winter-wheat regions hesitate to break up much of their hay land in the fall because new or young grass seedlings might winter-kill, leaving them without any hay crop.

Fall-plowed land should be left rough or unharrowed, unless a cover crop or winter grain is planted on it.

Fig. 51. Excellent stubble-land plowing.

Spring plowing. Spring plowing is most common, for the reason that spring is the principal planting season. Much depends on good plowing, for good tilth may have far greater effect on crop yields than any fertilizer. Seed-bed preparation is essential, whereas fertilizer may not be required. Too often the seed bed is ill prepared; its preparation should be regarded as something more than simply a routine farm operation (Fig. 51). In France a common maxim is, "A plowing gives a harvest."

Heavy soils may easily be injured if they are plowed too wet (Fig. 47). Sands, on the other hand, may be physically benefited by early spring plowing, especially those that are subject to "blowing."

Spring plowing for potatoes is usually preferable, especially for

good potato land, because tubers develop best in rather mellow ground. Moreover, the tubers grow smooth and shapely, and develop good quality.

Depth of plowing. Plowing to depths of from 6 to 8 inches generally gives most economical returns, as many tests have demonstrated. Although, in general, continual deep plowing has not proved to be economical, an occasional deepening of the plow furrow might be beneficial, particularly on the heavier and less productive soils. On the better soils, it may not be necessary to plow deeply for small grains—about 4 inches deep is usually better than 6 inches. On the poorer soils, however, fall plowing to a depth of 6 or 7 inches is generally better for small grains than is shallow spring plowing.

Varying the depth of plowing from year to year is regarded as a good farm practice. The reason is that if a soil is always plowed at the same depth, the tramping of the horses or the weight of the tractor on the bottom of the furrow tends to develop a so-called "plow-sole." This applies particularly to wet clay and clayey soils.

Dynamiting, deep tilling, subsoiling. Dynamiting has been done to break up and loosen impervious subsoils, and to facilitate the entrance of air, water, and plant roots. Although it may prove to be a good practice to meet hardpan conditions, as in tree planting, the value of dynamite for more general use has not been proved. Lime layers in some irrigated soils are broken by subsoilers.

Chilcott and Cole (1918) have published results of extensive dynamiting, deep-tilling, and subsoiling experiments which they have conducted at 12 stations in the Great Plains region, for a period of 5½ years at each station, and under average annual rainfall varying from 14.8 to 21.6 inches. The experiments covered a wide range of crops, soils, and conditions. From the data obtained, they have drawn the following principal conclusions:

1. Soil dynamiting, deep tilling, and subsoiling are operations that increase the expense of production, as compared with ordinary plowing, and they reduce the acreage that can be prepared by a given working unit. "Consequently, in order to justify their use, these practices should show increases in yields sufficient to pay for the extra expense involved."

2. Although there may be conditions that will give results favorable for these methods of deep tilling, the average yields obtained in these experiments "seem to warrant the conclusion that as a general practice for the

Great Plains as a whole, no increase of yields nor amelioration of conditions can be expected. . . ."

3. Subsoiling and deep tilling have been of no value in overcoming drought.

4. "Experiments conducted in the Great Basin under semiarid conditions with the greater part of the precipitation occurring in winter; under humid conditions in the States of Illinois, Pennsylvania, and Mississippi; under semiarid conditions at San Antonio, Tex.; and under semiarid conditions on the black soils of southern Russia have all led to the same conclusion: That yields cannot be increased nor the effects of drought mitigated by tillage below the depth of ordinary plowing."

Fallowing implies plowing plus after-cultivation, or plowing and harrowing without seeding, for the purpose of mellowing the land,

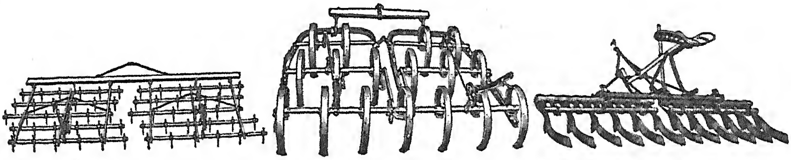

Fig. 52. Three types of harrows: left, a spike-tooth harrow; middle, a spring-tooth harrow; right, a blade harrow.

killing weeds and insects, and conserving the soil water. It may also mean the accumulation of soil nitrates. When this practice is followed during summer months, it is called "summer-fallowing." Fallowing is one of the oldest practices used in the cultivation of lands, one which originated in early ancient times. It was preceded by a much older practice: namely, reposing or resting lands. Bare-fallowing has become an established practice in modern dry-land farming, or agriculture under conditions of limited rainfall. (See Chapter 12.)

Pulverization and consolidation. After land is plowed, the soil must be pulverized and consolidated to form a seed bed. The principal implements used for these purposes are harrows, cultivators, and plankers, used primarily for pulverizing and smoothing. Rollers or packers are also used for crushing clods and for consolidating the soil material.

Harrows and cultivators operate practically on the same principle (Fig. 52). Tines or teeth are drawn through the soil material, and disks cut into the ground surface. Tines may be provided with replaceable points which may vary in shape from chisel

points to broad duckfoot shares, the latter being used for undercutting weeds as well as for pulverizing. Disks are especially suitable for use on hard ground and plowed turf land.

Full-disk harrows are most effective pulverizing implements (Fig. 53). When the ground is very hard and stony, and when it consists of plowed, tough turf, cutaway disks are often used. Spading disks may be used effectively on fields that are infested

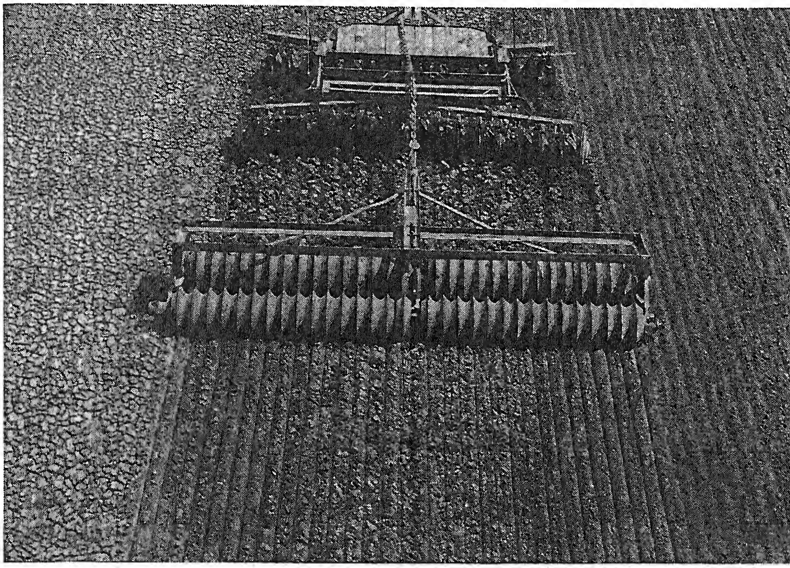

Fig. 53. A corrugated roller (following a double full-disk harrow), a most effective soil-compacting implement.

with quackgrass (quitch grass), for example, in order to bring the roots to the surface where they can be collected and removed. In some districts where the soils are loamy and free from stones, blade harrows are commonly used for pulverizing, compacting the seed bed, and for killing weeds. Springtooth harrows are particularly suitable for use on rough and stony land and on new land formerly covered with brush and tree growth. Drag or spiketooth harrows, which may be light or heavy, are used for pulverizing and smoothing the ground.

Rotary tillers have come into use, particularly for some types of tropical agriculture. Such a machine consists essentially of a series of tines which are made to revolve on an axis. An engine

supplies the motive power. This machine is used to pulverize the ground and to prepare a seed bed in one operation.

Rollers are of four principal types, namely, *smooth* or drum, *corrugated, tubular* or bar, and *crowfoot*. The first type may be made either of wood or metal (Fig. 53). Inasmuch as corrugated rollers leave the land surface ribbed, the surface soil material is not coalesced after heavy rains, but with a smooth surface the material runs together. It is for this reason that the ridge or ring rollers are preferred on heavy soils. They are also most effective machines to use for compacting sandy and loamy soils.

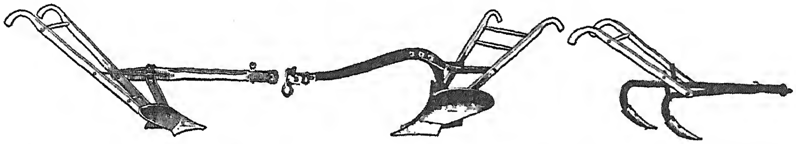

Fig. 54. Three implements commonly used in the southeastern States: left, a 1-horse or 1-mule turning plow; middle, a lister or middle-burster; right, a 1-mule, 2-shovel cultivator.

Middle-breakers. A middle-breaker, or middle-burster, is a kind of plow with an additional moldboard instead of a landside, used to throw up the earth equally on both sides (Fig. 54). This implement is commonly used in the southern States for bedding up land prior to planting cotton. The ridge forms a warm seed bed during the cool weather of early spring. Sometimes the first beds formed are broken open by middle-breakers, and crops are planted on the beds thus formed. Ridge or bed culture in producing cotton is also common in Egypt.

GOOD TILTH IN RELATION TO PLANTING

The four principal reasons why good tilth is an important factor in planting are: (1) the depth of planting may be better controlled by a compact seed bed; (2) movement of soil water from soil particle to soil particle and from soil particles to the seeds is facilitated by the compactness of the soil material; (3) seeds planted in soils having good tilth germinate quickly, provided temperature is favorable; and (4) the seedlings soon establish themselves as thrifty plants.

Small-grain and other small seeds may be planted too deeply as the result of a too loose seed bed. A grain drill may be set to

place seeds at a depth of about $1\frac{1}{2}$ inches; but if the machine is drawn over a very loose surface, the wheels may sink down 3 or more inches, and thus the seeds may be planted at a depth of $4\frac{1}{2}$ or more inches instead.

Seedlings that sprout from too deeply planted small seeds may die for want of air and from starvation, as the small quantities of food stored in the seeds may become exhausted before the shoots reach the surface, or on reaching the surface, they may soon die for lack of strength and want of food.

Conversely, too hard ground may prove to be as harmful as when the seed bed is too loose, though the effects are different. Here seeds may be left exposed and birds may devour them. Some seeds may sprout, but wither for want of moisture; and seedlings that may succeed in gaining an anchorage can make only poor growth, because of the unfavorable physical soil condition.

Pressing seeds close to soil material. Corn planters, beet seeders, cotton-planting implements, some grain drills, and other planting machines are provided with press wheels to establish close contact between the planted seeds and moist soil material.

Press grain drills are particularly effective implements for use on sandy soils, especially when high winds tend to blow away the soil material and thus expose and displace the seeds. Through the action of the wheels, the soil material is pressed around the seeds; this not only favors germination, but also holds both seeds and soil materials more firmly in place.

When very small seeds like those of grasses and clovers are planted, good tilth is a most important factor for successful germination and growth. Best results are obtained when such seeds are planted at shallow depths in firm seed beds, either broadcast or drilled. If broadcast, the seeds should be covered through the use of a light drag harrow, and the land then rolled to establish close soil-and-seed contact. If a smooth roller is used, it should be followed by "flat" dragging to create a mulch to lessen evaporation of soil moisture. The last two objects may be accomplished in one operation through the use of a corrugated roller. If a drill is used for seeding grass, clover, or alfalfa, compacting the seed bed after seeding may not be necessary; but if necessary, a corrugated, tubular, or crowfoot roller may be used.

Guiding principle in planting. That absorption of moisture by seeds and rootlets increases with close contact between seeds and

moist soil material and between rootlets and moist material is a guiding principle in planting and transplanting. It is known that seeds and rootlets in dry soils must exert a water-absorbing force as great as 1,000 atmospheres, whereas in moist soils they absorb water at only about eight atmospheres.

It is essential that seeds be placed at sufficient depth in the seed bed to assure adequate moisture for germination and subsequent plant growth. Usually seeds are planted deeper in dry soils and in soils of dry climates than in moist soils and in soils of moist climates.

In transplanting, close contact between soil material and the delicate roots of young plants can best be established through the use of water. Accordingly, transplanting machines are usually equipped with watering devices to enable the operators to apply a small quantity of water around the roots as each plant is set in place.

Unplowed seed beds. When small grain crops are planted on highly productive land, clean of weeds, comparative shallow disking has commonly proved to be more productive than spring plowing, in the preparation of the seed bed. This is particularly true of rich, black prairie and alluvial soils and crumbly silt loams on many dairy and livestock farms. It is the experience of many farmers that on seed beds thus prepared oats and barley stand up well and produce maximum yields. Furthermore, better growths of clovers and grasses result when they are seeded in with the grains thus planted in unplowed seed beds.

GOOD TILTH AND PLANT GROWTH

After planting, good tilth is a most important factor in root development and plant growth. Accordingly, modern implements have been devised for after-cultivation. Here, as in plowing, other objects may be attained in addition to good tilth, including destruction of weeds, aëration of soils, conservation of soil moisture, and providing loose soil material for earthing up plants, as in the culture of potatoes, cotton, and commonly of Indian corn. Two or more of these objectives may be attained in a single operation.

Cultivators and hoes. Various types of cultivators (commonly called "hoes" in Europe, and "plows" in the South) are used. Inasmuch as pulverizers and harrows operate on practically the same principle, cultivators may have tines, disks, and spikes, ac-

cording to the purpose in view. Tines may be provided with detachable and replaceable points which may vary in shape from chisel points, for digging, to broad duckfoot or knife-like shares, for undercutting weeds, as well as for loosening the ground surface, as in shallow cultivation.

Intertillage. After-cultivation consists mostly of intertillage—that is, cultivation of crops that are planted in rows. It may be done either by guiding the implement between the rows, as with walking cultivators, or by straddling the row, as with sulky cultivators.

In intertillage, the shovels or disks may be so adjusted as to move the soil material either toward or away from the plants—an important consideration in growing cotton and potatoes, and under certain conditions, in cultivating Indian corn.

Spike-tooth and 7-shovel walking cultivators are commonly used, particularly by gardeners. Two-shovel walking plows (cultivators) are common implements in the southeastern States (Fig. 54). Six-shovel (3-shovel gang) and 8-shovel (4-shovel gang) sulky cultivators have met with greatest favor, because of their general suitability. In extensive farming, cultivators that cover two and more rows at a time are often used.

Cultivation of crops not in rows. Sometimes conditions call for cultivation of small-grain fields, alfalfa, and grasslands, to loosen the surface soil layers, break up the crusts, and to aërate the soils. In grain fields, a light spike-tooth harrow may be used for this type of cultivation. For alfalfa and old sodlands, disk harrows meet the need, the type being determined by the condition or purpose in view. In places, cultivators with twisted knife tines are used for aërating old pasture lands, and *rejuvenators* with tines of various shapes are used to aërate grasslands by cutting or tearing the turf.

Weeders. Weeders are weed-killing and soil-mulching implements, which consist essentially of many narrow spring tines. They are suitable for loosening the ground and for killing very small weeds either before or after crop plants are up, and are effective implements to use on loamy soils. A light spike-tooth harrow may take the place of a weeder.

Emergency cultivation. Owing to rush of work, a farmer may not find time to compact the seed bed properly or break lumps before planting. If rains do not effect compaction, the land may

be rolled even after the crop is up 2 or 3 inches high, if it is a cereal crop.

Heavy rains often pack finely pulverized soil material so firmly as to cause the development of hard crusts which may prevent the penetration of plant shoots. A light cultivator, weeder, or light spike-tooth harrow may be used to prevent development of crusts or to break them.

When to cultivate. The proper time to cultivate is determined by moisture condition, weed growth, and special purposes in view. The best time to kill weeds is when they are small and when their seeds are germinating. Cultivation for good tilth is most successfully done under condition of optimum soil moisture. In the field this can be determined by the easy workability of the ground.

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REVIEW QUESTIONS

1. Discuss the importance of tilth in crop production.
2. Is tilth a natural or an artificial quality of soils?
3. How may good tilth be secured in the development of a seed bed of heavy clay? Of sand? Of sandy loam?
4. On what theory is the construction of plow moldboards based?
5. What principles would guide one in the use of rollers?
6. Why is good tilth important when seeding with a grain drill? Illustrate.
7. When may it be best not to plow lands for oats? Explain.
8. Discuss the importance of intertillage in relation to tilth and weeds.
9. What principle in soil fertility should guide one in the use of all tillage implements? Illustrate.

CHAPTER 12

SOIL WATER AND SOIL FERTILITY

The outstanding importance of water in plant growth cannot be too strongly emphasized, because in water all the complex chemical and physical processes essential to plant life take place (Ch. 9).

The quantity of water required by a plant for its composition or assimilation is insignificant when compared with what it absorbs and transpires during its growth. The quantity required during growth is called "water requirement," or "transpiration ratio," which is the average quantity of water necessary to produce 1 pound of dry plant substance. In crop production, soils function as water reservoirs; and in regard to soil productivity, the water functions as a soil-fertility factor.

Water problem in soil fertility. The water problem in crop production, in harmony with the principle of soil fertility (see Index), may be stated as follows: To meet the water requirement of plants through soils in a manner that will best satisfy the plant needs in accord with principles of farm economy. An understanding of this problem depends in a large measure on a knowledge of certain fundamental facts and principles regarding soils and crop plants, and the relation between them.

FUNDAMENTAL FACTS PERTAINING TO SOIL WATER

Available water and growth. In general, available soil water is the difference between the point of field moisture capacity and the permanent-wilting point, or between pF 3.2 and pF 4.2 (Ch. 2). But this does not mean that plants can absorb available water with equal effort from the point of field moisture capacity down to the permanent-wilting point. Crops may grow and yield best when abundant water is available during early growth, or irrigation may be beneficial long before the wilting point is reached.

Available water. Field moisture capacity varies widely, from 15 percent in a coarse sand (wt. dry soil, basis) to 45 percent in a black silt loam, as determined by such factors as texture, organic

matter, structure, and especially subsoil. These percents are equivalent to 3.2 and 6 surface inches[1] per cubic foot of soil, of which plants can use 3 and 4 acre-inches per acre-foot of soil (Ch. 2). In some instances, as most of the sugarcane soils of Hawaii, only about 25 percent of the field moisture capacity is available.

Sources of water. The principal sources of soil water for plants are precipitation, storage water (irrigation), and ground water.

Precipitation varies from only a few to more than 50 inches of annual rainfall, giving rise to four types of climate: *arid* or desert, ordinarily with less than 10 inches of rainfall; *semiarid,* between 10 and 20 inches; *subhumid,* between 20 and 30 inches; and *humid,* with 30 and more inches of precipitation. These ranges hold for low altitudes.

The main factors that control geographic distribution of rainfall are distance from principal sources of water (seas, lakes, etc.), topographic features, and location with reference to paths of frequent cyclonic storms. In places these factors operate singly, while in other places two or all three factors may act conjunctly.

Within the different climatic regions, the rainfall-distribution factors operate in such manner as to give rise to different types of seasonal distribution of rainfall. In some regions the precipitation is distributed rather equally for each month, as in the eastern United States; in some regions the greater part of the precipitation occurs during the summer months, as in the Dakotas, Minnesota, Iowa, Kansas, and Nebraska; while in other regions the distribution is characterized by very light summer and high winter rainfall, as in Washington, Oregon, and California.

Ground water, that is, water which supplies low areas by seepage or which is supplied to crops through a controlled ground water table, has made possible, in places, the production of exceptionally high crop yields. Irrigation is discussed in the following chapter.

How water passes out of soils. Much of the water that is naturally and artificially added to soils is lost or passes out of them without benefiting the crops, for three principal reasons: (1) Soils have only limited water-retaining power, and hence a great deal of the water percolates through them. (2) A large part of the

[1] One inch of water on 1,000 square feet is equivalent to 623 gallons. One inch of water on one acre (43,560 sq. ft.) is equivalent to 113.43 tons of water. One cubic foot of water weighs approximately 62.5 pounds.

rain water does not enter the soils at all, but flows away as surface run-off. (3) The physical laws that govern the evaporation of water from the ground surface are always operating. Enormous quantities of soil water pass out of growing plants through transpiration.

Loss of water through percolation. Loss of rain water through percolation is greatest on level, well-drained, uncropped lands. This loss, in humid regions, has been found to vary from about 40 to 66 percent of the total annual precipitation, or an average loss of about 50 percent, under uncropped conditions. Under cropped conditions, this loss may be reduced about 25 or more percent.

In the winter months, at Rothamsted, England, the percolation loss has been as much as 80 percent of the winter rainfall, and in April has amounted to a little more than 20 percent. It has been observed also that when the ground becomes dried out to any depth during summer, percolation may be hindered considerably by soil air and the absence of film moisture, the film water being an important factor in aiding the downward movement of water through soils.

In regions of limited rainfall, there is very little or no rain water lost by percolation.

Loss by transpiration and evaporation. Water that goes out of soils through growing plants, or by transpiration, may be regarded as beneficial water. Probably one fourth of the precipitation of some humid regions passes through crop plants during the growing period.

At Geneva, N. Y., the loss of rain water through percolation on one loam, cropped with alfalfa, timothy, and small grains, has averaged 25.7 percent of a total annual rainfall of 35.4 inches. On another loam, growing the same kinds of crops, loss through percolation has averaged 19.2 percent of the total rainfall. Accordingly, 74.3 percent of the rain water, or 26.3 inches, and 80.8 percent, or 28.6 inches of rain water, respectively, have been lost from the two soils through transpiration and evaporation.[2] In the Geneva 12-year tests, practically no drainage from the lysimeters occurred during the growing season when crops occupied the soils.

At Ithaca, N. Y., on a silty clay loam (*Dunkirk* series) cropped with maize, small grains, and hay, about 33 percent of the water

2 Collison, R. C., and Mensching, J. E. LYSIMETER INVESTIGATIONS. New York State Agr. Expt. Sta., Geneva, Tech. Bull. 166. 1930.

of an annual precipitation of 32.52 inches was lost through transpiration and evaporation, of which 18 percent was lost through transpiration.

In semiarid regions, where fallowing is practiced, the loss of soil water through transpiration and evaporation in 2 years commonly exceeds the total annual rainfall.

Loss of rain water in run-off. Natural surface drainage may be responsible for very high percentage losses of rain water, owing to steep slopes, soil conditions that do not favor absorption of water, and heavy rains. On the "rolling" lands of the eastern third of Nebraska, it has been estimated that the average annual run-off amounts to from 30 to 40 percent of the total precipitation which varies from 24 to 32 inches.[3]

Capillary rise of soil water. It was pointed out in Chapter 2 that capillary rise of soil water has been greatly overemphasized, and that it is not so important a factor in crop production as early investigators had supposed. Keen (Eng., 1928) has found that capillarity is practically negligible at a distance of 3 feet. Furthermore, with crops in humid regions, upward movement of soil water can become effective from a point only about 3 feet below the root zone during a prolonged dry period (Ch. 2). Accordingly, the ground zone from which crop plants may obtain their water is about 6 feet deep, and taproots draw up water. In semiarid regions the movement of soil water takes place mostly within the first 4 feet. Sen (India, 1930) has observed that, as the dry season advances, the upward movement of moisture in Indo-Ganetic alluvial soils commences at the surface; and as the water is absorbed by plants or evaporates, it rises from lower and lower depths, slowly to be sure, and the movement ultimately reaches a depth of about 5 or 6 feet.[4]

Breazeale and Crider (1934) have demonstrated that, under semiarid conditions, plants may absorb water from one soil zone, where it is available, and exude it into another zone, where it is scarce.

WATER REQUIREMENT OF CROP PLANTS

The earliest studies of water loss by plants were made by Wood ward (Eng.) in 1699. Hales (Eng.) conducted tests on transpira tion as early as 1731-1733, with a view to making a practical appli

[3] Nebraska Agr. Col. Ext. Circ. 133. 1931.
[4] Memoirs Dept. Agr., India, Chemical Series 10, pp. 221-235. 1930.

Crop	Lawes, Rothamsted, Eng., 1850	Wollny, Munich, Ger., 1877	Hellriegel, Dahme, Ger., 1883	King, Madison, Wis., 1892-1893	Von Seelhorst, Göttingen, Ger., 1899-1910	Widtsoe, Utah, 1909	Leather, India, 1910, 1911, cool-weather conditions	Briggs and Shantz, Akron, Colo., 1913-1915	Kiesselbach, Lincoln, Neb., 1910, 1916	Thom and Holtz, Pullman, Wash., 1917	Richardson, Victoria, Australia, 1923	Dillman, Newell, S. Dak., and Mandan, N. Dak., 1931
	Pounds of Water Required to Produce 1 Pound of Dry Plant Substance											
Alfalfa	—	—	—	—	—	—	—	626* to 1,168	—	—	790.5	798 to 887
Barley	258	774	297	388	365	—	468	400 to 686	—	325	350	—
Buckwheat	—	646	371	—	—	—	—	416 to 659	—	—	—	—
Clover (red)	251	453	330	481	—	—	—	584 to 926	—	—	—	—
Maize	—	233	—	350	—	386	337	212 to 516	463 327 384	231	—	—
Oats	—	665	401	541	—	—	469	370 to 876	—	313	390	536
Peas	235	416	292	477	—	843	563	788	—	385	344	—
Potatoes	—	—	—	423	281	—	—	329 to 744	—	—	—	—
Wheat	235	—	359	—	333	546	554	419 to 869	—	375	380	403 to 460

* Summary by Shantz, H. L., and Piemeisel, L. N. 1927.

cation in agriculture. Lawes (Eng., 1850) was the first investigator to study transpiration for the whole period of plant growth. Since 1850, scientists in different countries have studied the water requirement of different agricultural plants under different climatic conditions. The results for the more common plants are summarized in the table on p. 227.

The essential features of the methods used by these investigators consist in growing plants in pots or cylinders and determining the number of pounds of water consumed during the vegetation period (care being taken to allow for rainfall and loss by evaporation of water from the soil surface), and also in placing the plants as near as possible under the same atmospheric conditions as in the open field. When such a test is completed, the total weight of dry plant substance produced is ascertained by weighing the plants as soon as they are harvested and thoroughly dried. From these data, the average quantity of water (pounds) that has been used in producing 1 pound of dry matter can be easily calculated. Only in case of root crops is the weight of underground parts included.

King made no attempt to check surface evaporation, nor did he make any correction for this. Thus his results may be regarded as inconclusive.

Hellriegel found that water requirement varied with the crop, water content of soil, and kind of fertilizer used.

Widtsoe found that crops grown in unproductive soils had higher water requirements than those grown in fertile soils.

Leather observed that water requirement of a given crop varied widely on different soils, probably because of the effect of nutrients, and that fertilizers reduced transpiration. Results reported by Leather in the table on p. 227 are for fertilized plants.

Briggs and Shantz conducted their investigations under semiarid conditions (from 15 to 20 inches of rainfall, average annual nearly 18), and with over 100 different kinds and varieties of plants.

Kiesselbach, working under conditions of a humid climate (about 30 inches of rainfall), studied all factors that affect water requirement of crop plants. He used Indian corn as a type plant, growing it in soil materials that represented an infertile soil (*Lancaster fine sandy loam*), a fertile soil (*Wabash silt loam*), and an intermediate "soil" (mixture of first two materials). The average results given in the table were obtained under unmanured conditions.

Corresponding results under manured conditions are 323, 298, and 308, or 30, 9, and 20 percent less.

Thom and Holtz conducted their inquiry in a district having an annual rainfall of about 20 inches. They found that it required, on the average, 312 pounds of water to produce 1 pound of dry matter in 6 cereal crops, and 429 pounds in 4 legumes. Crops that took soil moisture from the greatest depths also had the greatest water requirement. They reported, too, that transpiration decreased with increase in concentration of soil solutions.

Richardson's results (those given) were obtained in a subhumid climate with an average annual rainfall of 21.5 inches. Four-year results showed that transpiration ratios varied closely with the rates of evaporation during the period of maximum transpiration. Richardson also observed that transpiration ratios varied from 660 to 1,188 for six different varieties of wheat.

Factors affecting water requirement. Transpiration may be affected by several factors which, according to Kiesselbach, may be classed as atmospheric or climatic, soil, and plant.

Climatic factors include temperature, relative humidity, wind, light, radiant heat, composition of air, and air pressure, the total effect of which in a given region may be expressed as *rate of evaporation* from a free water surface. This rate of evaporation, according to Briggs and Belz (1910), may vary from 24 to 72 inches annually.

The relation between climatic factors and water utilization may be illustrated by the growth of native short grasses (buffalo and grama), typical of the semiarid part of the Great Plains, whose habitat is a zone extending from Texas to Montana. The annual precipitation in the Texas part of this grass zone is 21 inches, while in the Montana part it is 14 inches, the difference being due to evaporation. According to Burr (1931), a 15-inch rainfall in North Dakota may have crop-producing value equal to 25 inches of precipitation in the southern part of the Great Plains.

Soil factors include composition, texture, content of available moisture, concentration of soil solution, and soil temperature. Plant factors are root development, leaf area, structure of leaf, arrangement of leaves, density of cell sap, ability to withstand periods of drought, age, moisture, content of leaf, and disease. The result of all plant factors may be expressed in the quantity of dry substance produced.

Practical significance of water requirement. The practical significance of water-requirement data may best be expressed in terms of the quantity of water required to produce 1 unit of produce or a given yield. In a humid climate, on productive soils, about 150 barrels of water must pass through the plants to produce 1 bushel of Indian corn; about 140 barrels are required to produce 1 bushel of oats or barley; and between 2,000 and 3,000 barrels of water are required for each ton of alfalfa hay.

On the basis of 150 barrels of water per bushel of Indian corn, it would require about 13 acre-inches of water during the growing season to produce a yield of 75 bushels an acre. If only 7 inches of water were available, the yield would probably be only about 38 bushels, other conditions being equal. Under southern California irrigation conditions, Beckett and Dunshee (1932) found that a full stand of cotton on sandy loams used 24.5 inches of water per acre.

According to the field data obtained at Pullman, Wash., Thom and Holtz (1917) have estimated the total number of inches of water required to produce the average yields that were obtained on the field plots, as follows:

WATER REQUIRED FOR CROP YIELDS IN EASTERN WASHINGTON
(Three-Year Averages)

Crop	Yields per Acre		Loss of Water per Acre			Total Quantity of Water Required
	Grain	Straw	Rain Water	Evaporation	Transpiration	
	Bushels	*Tons*	*Inches*	*Inches*	*Inches*	*Inches*
Beans	9.7	0.51	3.15	2.48	3.60	9.23
Maize	33.4	1.88	3.15	1.84	4.30	9.29
Millet	—	2.75	2.45	2.25	7.68	12.38
Peas	31.5	1.27	3.30	1.80	7.47	12.57
Barley	48.4	1.64	3.30	1.98	8.79	14.07
Oats	85.0	1.72	3.30	2.46	9.97	15.73
Wheat	44.2	1.86	3.30	3.36	12.74	19.40

On the basis of the results obtained under a climate of 20.5 inches of rainfall, Richardson (1923) has calculated the average crop yields produced per acre for each inch of seasonal rain transpired by the crop plants, as shown in the table on the opposite page.

In their study of the water requirement of spring wheat on the Great Plains, Cole and Mathews (1923) have found that yield is not directly proportional to the total quantity of water used. A certain quantity, varying from 4 to 10 inches, is necessary for

consumption before any yield is realized. Above this minimum, each unit increase of water consumed seems to result in a unit increment of yield (Fig. 55).

YIELDS PRODUCED FOR EACH INCH OF SEASONAL RAINFALL

Crop	Quantity of Rain to Produce		Yield per Acre for Each Inch of Rain Transpired
	One Ton of Dry Matter	One Ton of Grain	
	Inches	*Inches*	*Bushels*
Wheat (summer grown)	6.69	17.34	2.15
Wheat (winter grown)	4.04	10.25	3.63
Oats (winter grown)	4.31	12.65	4.42
Barley (winter grown)	3.33	7.55	5.93
Alfalfa (lucerne)	6.71	——	——

Two general plant facts. Inquiry into water requirement of plants has established two important facts regarding water relations: (1) different species and varieties of plants differ greatly

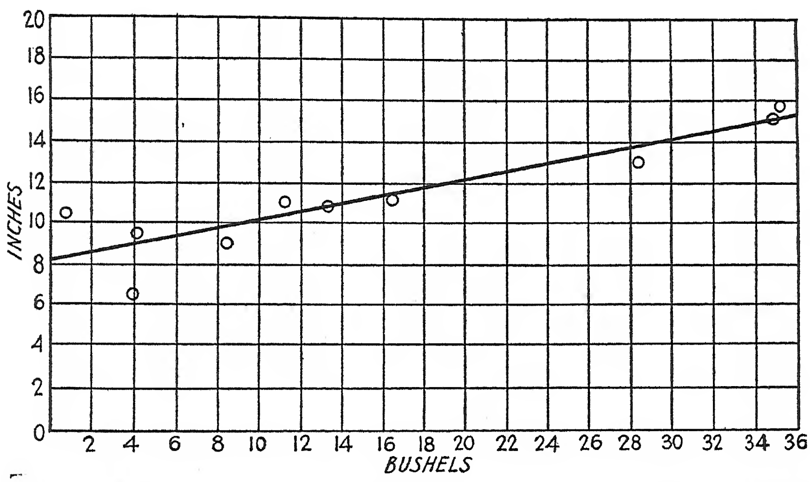

Fig. 55. Relation between quantity of water used and yield of spring wheat, in which is shown a minimum of 8.16 inches of water necessary for consumption before any yield is realized. Above this minimum, each unit increment of water consumed resulted in a unit increment of yield.

in their water requirement; and (2) absorption of nutrients by plants takes place independently of the absorption of water.

Principles pertaining to water relations. Inquiry into both soils and water requirement of plants has resulted in the discovery

of four principal facts regarding water relations between soils and agricultural plants:

1. When other conditions are favorable, crop yields, within certain limits, depend largely on the quantity of available water that soils contain during the growing season.
2. For each textural type of soil there is a definite percentage of moisture that is absolutely necessary for the existence of crop plants and below which water cannot be absorbed by the plants in sufficient quantity for continued growth. This percentage of water has been designated as the "wilting coefficient."
3. Water requirement, or transpiration ratio, is not a definite and constant quantity for a given plant, but varies according to soil and atmospheric or climatic factors.
4. Within certain limits, plants growing on soils that are well supplied with available plant nutrients require less water than when growing on poor or infertile soils.

CONTROL OF SOIL WATER

The problem of water control or efficient use of water in relation to soil fertility concerns both plants and soils. Under natural conditions, in humid, subhumid, and semiarid regions, rain water can be controlled within only rather narrow limits. This problem is discussed in relation to soil fertility in the three regions mentioned. The subjects of irrigation and land drainage are reserved for the next chapter.

WATER CONTROL IN HUMID REGIONS

Plant factors. There are four principal plant factors concerned in the control of soil water or in its economical use in humid regions, as follows: plant nutrition, plant adaptation, time of planting, and thickness of stand or quantity of vegetable growth.

Investigators have established the general fact that plants grown on fertile soils or those that are properly fertilized have lower water requirements than the same plants grown on poor or infertile soils. This fact was observed by Lawes in 1850, when he found that chemical fertilizers reduced the average transpiration ratio for wheat, barley, and clover from 258 pounds of water per pound of dry matter to 209 pounds, a decrease of 19 percent. Liebscher (Ger., 1895), working with oats, observed that complete fertilizers gave a lower water requirement on both sand and clay than on unfertilized pots. Wimmer (Ger., 1908) found that nitrogen, in pot

tests, lowered the transpiration ratios of chicory, ryegrass, beets, and carrots. In one experiment, Widtsoe (1909) reduced the transpiration ratio of maize from 908 to 464 by adding manure. Leather (1910) observed that nutrient elements was an important factor affecting water requirement, and that liberal use of fertilizers reduced the transpiration ratio.

Kiesselbach (1916) has reported a 29 percent lower water requirement for maize grown on fertile than on infertile soil. Where he applied manure at the rate of 21 tons an acre, the water requirement was reduced nearly 9 percent on the fertile soil (from 327 to 298 pounds of water per pound of dry matter) and more than 30 percent on the infertile soil (from 463 to 323 pounds). (See p. 227.) Accordingly, development of nitrates in soils might prove to be of greater importance than conservation of soil water in crop production in humid regions.

From results he obtained in Victoria, Australia, Richardson has concluded that suitable fertilizer is an important factor in the control of transpiration ratio.

At Geneva, N. Y., Collison and Mensching (1930) have reported an 11-percent average decrease in water utilization by alfalfa, barley, and wheat which were fertilized with nitrogen, as compared with crops that received no nitrogen (all crops received standard applications of phosphate and potash).

Adaptation of a crop in relation to soil-moisture economy may be illustrated in growing winter rye on sandy soils. When sown in the fall, particularly in northern regions, this crop may become well established before winter weather sets in, so that when growth is renewed in the spring, the crop is able to make the most efficient use of the soil water. With some crop plants, certain varieties have proved to be more efficient in water utilization than others.

Time of planting, as a factor in the efficient use of soil water by crops, may be illustrated in the planting of spring wheat, oats, and barley, particularly in regions in which dry periods commonly occur about heading time. Planting these crops as soon as soil and temperature conditions will allow has proved to be the best and most productive farm practice. Under certain conditions, as on sandy soils, planting less seed per unit area of land than is ordinarily planted may be helpful in effecting more economical or productive use of soil water, because then there will not be so many plants to draw on the limited water supply.

Soil factors. In humid regions, control of water for crop use consists principally in reducing the loss of rain water, which occurs through surface run-off, percolation, and evaporation from the ground surface. This may be accomplished by aiding soils to catch and absorb more rain water, increasing their water-retaining power, and by reducing the evaporation loss.

Aiding soils to absorb rain water. Soils may be made to catch or trap rain water in the following ways: (1) by plowing, to create a loosened surface; (2) by leaving fall-plowed and fall-planted lands rough, to aid water absorption; (3) improving soil structure through the use of organic fertilizing materials and carbonate of lime, as on heavy soils, to aid penetration of water; and (4) by contour plowing and planting on steep slopes, to allow more water to soak into the ground.

Increasing water-retaining power. The water-retaining power of soils is determined principally by their mechanical composition and content of organic matter. Inasmuch as the mechanical composition of soils cannot be modified to any appreciable degree, their water-retaining power cannot be improved by modifying their texture. However, the maintenance of organic matter may prove to be beneficial by preventing the break-down of soil structure or by improving it. It has been shown that, of two soil materials of the same mineral and organic composition, the one having crumby structure has the higher water-retaining power (Ch. 2).

Reducing evaporation loss of soil water. Loss of soil water by evaporation may be reduced by getting rid of weeds and by the use of mulches. Inasmuch as weeds, like crop plants, require large quantities of water during vegetable growth, their destruction is an important factor in moisture conservation. Wollny obtained a water requirement of as much as 843 pounds of water for mustard weeds. For the same kind of weed, Leather obtained a requirement of 496 pounds. According to Shantz and Piemeisel (1927), tumbleweeds (*Amaranthus græcizans*) and redroots, or pigweeds (*Amaranthus retroflexus*), have water requirements of 260 pounds; and lambsquarters (*Chenopodium album*), 658 pounds.

On many soils, the primary object of after-cultivation, or intertillage, is to kill weeds. The best time to do this is when the ground is in good condition to till, and when the weeds are small.

Results of depth-of-cultivation tests that have been conducted in humid regions are in favor of comparatively shallow cultivation. It has been found that much injury can be done to the absorbing organs (roots) of plants by deep intertillage.

For many crops, level cultivation is the best practice, provided weeds are killed when they are very small; otherwise hilling is necessary to cover them. Many tests have shown that hilling Indian corn has no advantage over level cultivation, except possibly to cover weeds.

Soil mulch for conserving water. In cultivation, two principal objectives may be attained in a single operation. The ground surface is loosened and weeds may be destroyed. A loosened layer of soil material, which soon becomes dry, is called a "soil mulch." It may serve four purposes: It may maintain a more uniform temperature of the soil material immediately below; it may reduce evaporation loss of soil water; it may aid soil absorption of rain water; and it may increase the efficient use of water by the plants.

Efficiency of soil mulch. From his studies of soil mulches, King (1885-1900) found that they were effective in reducing loss of soil water by evaporation. His results gave rise to the belief that, generally, soil mulches that resulted from cultivation reduced evaporation losses and thereby conserved soil moisture. Subsequent inquiry into the problem of soil mulches, however, has shown conflicting results. Some investigators have concluded that cultivation is beneficial chiefly in killing weeds.

A summary of results of many cultivation tests would indicate no beneficial effects of cultivation, except possibly to kill weeds. Cates and Cox (1912) have conducted co-operative cultivation tests with farmers in 28 States, in which yields of Indian corn obtained from ordinary cultivation were compared with those obtained on plots on which the weeds were cut by scraping the ground surface with a hand hoe, with the least disturbance of the soil material. On the basis of average yields, they concluded that cultivation was not beneficial to corn, except for killing weeds. In Pennsylvania, Merkle (1930) has obtained similar results.

Conclusions based on average yields of all cultivation tests, however, have neither practical nor scientific value, any more than average results of all fertilizer tests would have. For example, a summary of results of 3,227 fertilizer tests on wheat, reported in

experiment station publications, shows that the "average" increase obtained did not pay for the average fertilizer treatment. In cultivation experiments and in soil management, consideration should be given to the soil, weather, and climatic factors.

On loam soils of granular and crumby structures, protective crusts may develop in dry seasons, as the result of rapid surface evaporation. Such crusts break the connecting films of soil water, and thus protect the water from evaporation. Under the same conditions, natural mulches of sand layers may develop on sandy soils, and surface layers of dry peat and muck materials on marsh soils. On the other hand, heavy soils, on drying, do not, as a rule, develop protecting crusts, but become very dry and hard, and crack.

Furthermore, during seasons of frequent rains, soil mulches may prove to be of little or no value on any kind of soil. To determine the real value of a good soil mulch, it would seem that tests should be conducted during long dry periods, particularly on the heavier soils. To illustrate:

In a test on a heavy silt loam (*Miami* series) in Wisconsin, conducted with a view to determining the value of a good soil mulch, Weir (1908) obtained an increase of nearly 68 percent in the yield of maize through the use of such a mulch in a season in which no beneficial rains occurred during the critical growth period between July 3 and August 12. His results, rejected (with others like them) by Cates and Cox, are as follows:

EFFECT OF CULTIVATION ON YIELD OF MAIZE

Cultural Method	Character of Growth	Rated Quality of Corn	Yield per Acre
		Percent	*Bushels*
Plot 1. Weeds cut with a sharp hand hoe; soil material stirred to the least possible degree.	Uneven	70.0	44.6
Plot 2. First two cultivations 3½ inches deep; subsequent cultivation shallow, and as often as was necessary to kill weeds and maintain a good soil mulch.	Excellent and uniform	99.5	74.8

During a dry summer following a wet spring, Ullsperger (1916) obtained the following yields of soybean hay on sand at Hancock, Wis., during a season in which very little rain occurred between June 30 and August 15:

EFFECT OF CULTIVATION ON YIELD OF SOYBEANS

Cultural Method	Yield, Pounds per Acre
Plot 1. Weeds were cut with a hand hoe; soil material stirred as little as possible.	1,875
Plot 2. Frequent cultivation.	3,660

The conclusion is that on heavy and sandy soils, evaporation of soil water may be controlled to a considerable degree through cultivation, particularly during long dry periods.

An effective soil mulch. A layer of dust is not a desirable soil mulch, because it may blow away, and it may become a hard crust through the combined action of rain water and sun. Generally, an effective soil mulch on a sandy soil may consist of a 3-inch layer of loose, dry sand; and on loams, silt loams, and clay loams effective mulches should consist of about a 3-inch layer of crumbs or a mixture of crumbs and small lumps.

Excessive cultivation during dry seasons may prove to be harmful to crops, especially when there are no weeds to kill and when a good mulch has already been made. A good practice in cultivation is to begin when the plants are young, before they spread their roots, and to dig, "plow," or "hoe" fairly deeply. When the roots begin to spread, the depth of cultivation should be reduced. Whenever, on examination, the tines or shovels nearest the plants dig too deeply and tear the roots, they should be raised or set for more shallow digging.

Other kinds of mulches. Materials like peat moss, straw, paper, manure, leaves, and grass are used for shrubs, on small areas, and for plant beds, not only for conserving soil moisture but also for control of weeds and soil washing, for fertilizing purposes, and for ground and plant protection (see Index).

The use of paper for mulching gives promise of usefulness for weed and disease control and for the stimulation of the plants, particularly of quickly maturing vegetable crops. New paper has to be used each season.

Other factors affecting soil moisture. Slowness of movement of soil moisture and absorption of water by plant roots probably are effective factors in controlling loss of soil moisture by evaporation. Absorption by roots probably causes movement of film water counter to the upward movement that evaporation may cause in

the surface layer of a soil, inasmuch as roots of plants are in continuous contact with films of soil water.

In selecting orchard sites, it is important to consider the nature of subsoils. Hardpan and subsoils of gravel and coarse sand affect unfavorably not only root development but also the water supply. Compactness of the seed bed and close contact between the seed bed and soil material immediately below are other factors that affect soil moisture, by favoring its movement in soils.

During their vegetable growth most agricultural plants have critical periods in which the water supply becomes a most important factor in determining yields. With small grains, this critical period is about the heading time; with Indian corn, about the earing stage; and with potatoes, when tubers begin to set. In many places where intensive farming is practiced, irrigation is used to supplement precipitation during these critical periods.

WATER PROBLEMS IN SUBHUMID REGIONS

Although in regions that have from 20 to 30 inches of average annual precipitation the problems of moisture control and its economic utilization are similar to those in humid regions, there is a special problem concerning the application of the basic fact that available nutrients decrease the water requirement of plants. This problem is typically illustrated in growing Indian corn: Increasing the supply of available nutrients in a soil decreases the average quantity of water required to produce 1 pound of dry substance. But as well-nourished plants grow more luxuriantly and produce a greater yield than those that are insufficiently nourished, a greater total quantity of dry matter is produced, necessitating a greater total quantity of water. Thus if the moisture supply is limited, increasing vegetable growth by fertilizing may actually cause a deficiency of soil water and a consequent reduction of yield. To meet this problem, if the moisture supply is limited and fertilization is necessary, the number of plants per unit area may be reduced. Growing a smaller variety of corn is another method. Listing corn is a rational practice in regions of limited rainfall, particularly on fertile soils.

Listing corn. A lister is a double-moldboard plow which makes a deep furrow, and at the same time plants and covers seeds (usually maize and sorghum) in the bottom of the furrows which intervene between ridges. Planting corn in this manner tends to

check the rate of growth and leaf development without proportionately reducing ear development, thereby conserving the water supply for a longer period and making possible normal maturity of the crop.

Effect of one crop on another. In subhumid regions, one crop, on using a large quantity of water, may cause a deficiency of water for the crop that follows. Alfalfa is a good example, except on irrigated lands. Maize on alfalfa sod often suffers for want of sufficient water for two principal reasons: (1) mature alfalfa, whose roots grow deeply, dries out the subsoil more than other crops, and (2) alfalfa residues increase the vegetable growth of corn, thus creating a demand for a greater quantity of water.

Water supply and crop yields. Kiesselbach (1916) has shown the relation between rainfall and crop yields in a subhumid region, as in the eastern part of Nebraska, in the following manner: A 50-bushel yield of maize (all stalks bearing) would use 9.3 acre-inches of water. A 13-year average yield of maize at the experiment station at Lincoln is 46 bushels. The average annual precipitation in eastern Nebraska is about 28 inches, two thirds of which is lost in other ways than by transpiration. Thus about 9 inches of the rain water in this part of the State is the quantity available for Indian corn. Accordingly, so far as corn yields are concerned, eastern Nebraska has a "50-bushel" climate.

From Iowa westward, maize growing is limited, first by rainfall, and second by short growing seasons which result from increased altitude.

In the Washington-Idaho subhumid region of 18 and more inches of rainfall, summer-fallowing for the purpose of using water of two seasons for the production of one crop is, according to Sievers and Holtz (1923), without scientific basis. As an annual rainfall of between 18 and more inches is sufficient to supply the soils with about 12.5 acre-inches of available water necessary to meet the requirements of a 40-bushel wheat crop, summer-fallowing would practically mean a loss of an equivalent quantity of rain water through percolation.

SOIL WATER IN DRY FARMING

Dry farming has come to mean the production of crops without irrigation in regions of deficient rainfall, such as those having from 10 to 20 inches. This type of farming, as developed in North

America, began in the State of Utah about 1863,[5] and its practice has increased rapidly since 1900. The semiarid or dry-farming region of the United States includes parts of 10 States and embraces 450,000 square miles of territory between the 98th meridian and the Rocky Mountains, and also extends for some distance over the Canadian border (Fig. 56).

In semiarid regions where irrigation is not now practicable, dry farming enables the fullest use of drought-resisting wheats in extending the wheat-growing area, wheat being the principal crop. Wheat produced under dry-farming conditions is rich in protein and gluten, and the grains are flinty and rather transparent; whereas under irrigation, the kernels are light colored, opaque, starchy, and soft. The yields of wheat obtained in dry farming are not so large as under irrigation, but the quality is better.

Two principal water problems are involved in dry farming:

(1) to obtain the largest possible supply of soil water; and (2) to grow crop plants that can withstand drought—that is, deficiency of soil water which is usually accompanied by atmospheric conditions that induce high rate of evaporation. Soil water, in dry farming, is alternately abundant and scant; therefore the most successful crop plants are those that can adjust themselves to these alternations.

Although annual precipitation is commonly regarded as the most important factor in dry farming, distribution of rainfall (seasonal, monthly, and daily) may be even a greater factor. Arable soils in semiarid regions are usually very productive when climatic conditions are favorable (Fig. 57).

Plant factors. Plants adaptable to dry farming include those that have the ability to become partly dormant during a drought; during this time such plants make very little demand upon the soil water, because transpiration practically ceases. Grain sorghums are good examples.

The development of crop plants that can utilize a limited quantity of water most economically and profitably is a problem that offers excellent opportunities in agronomic research. With some crops, the growing period has already been shortened by as much as 10 days. In "dry-land" maize, early maturity and resistance to drought have been obtained in plants that have shorter and less leafy stalks than ordinary corn.

5 BRAKEN, A. F., and STEWART, GEORGE. A QUARTER CENTURY OF DRY-FARM EXPERIMENTS AT NEPHI, UTAH. Utah Agr. Expt. Sta. Bull. 222. 1930.

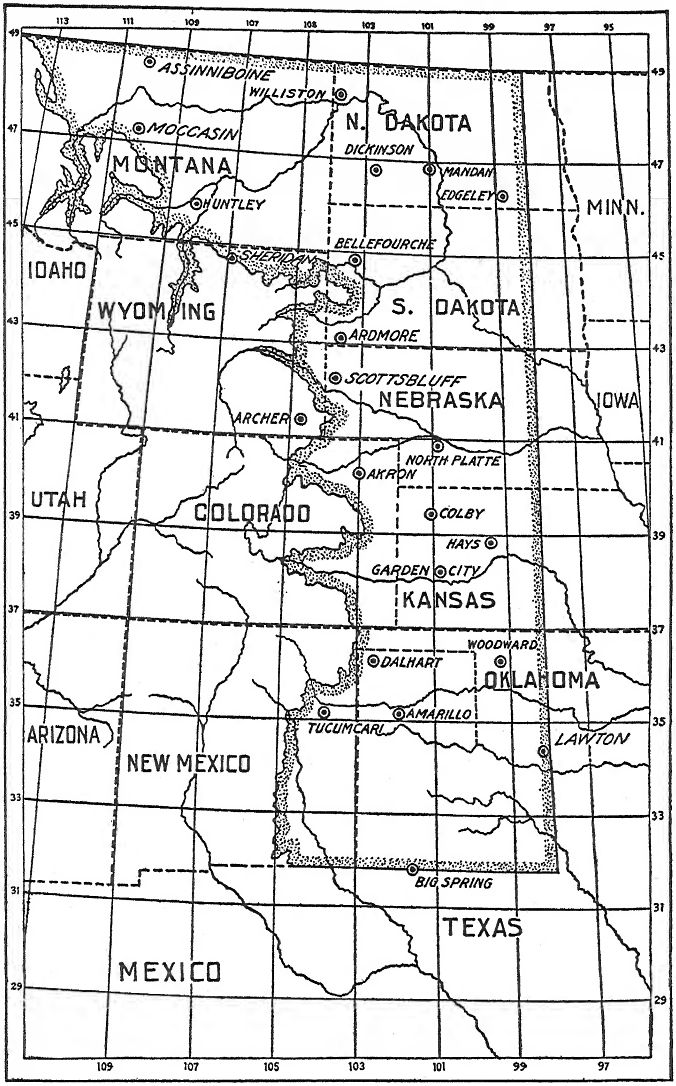

Fig. 56. The dry-farming region of the United States, including 450,000 square miles of territory between the 98th meridian and the Rocky Mountains.

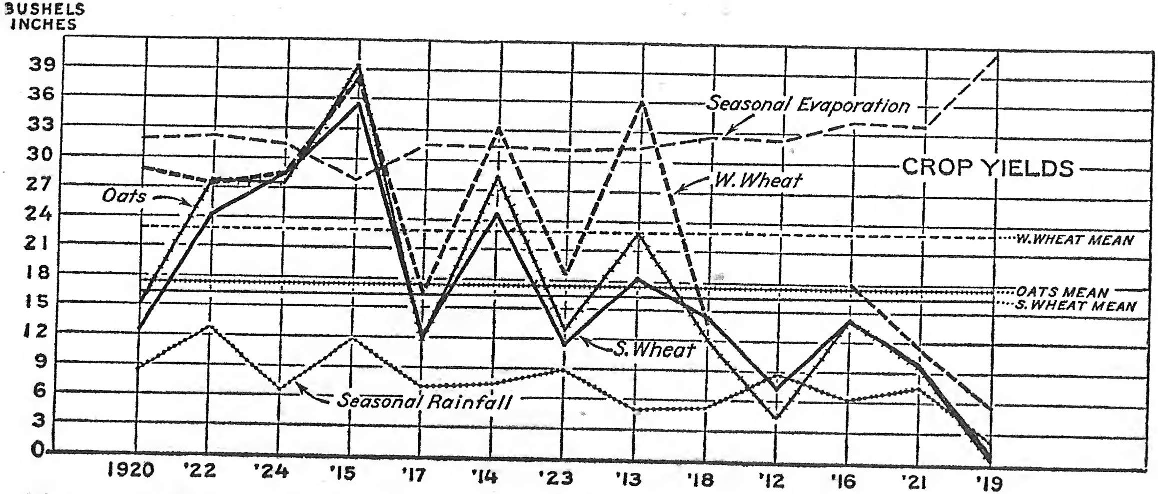

Fig. 57. Relation between rainfall and crop yields at Huntley, Mont. In 1915 and 1922, the marked increases in crop yields resulted not only from increase in seasonal precipitation but also from favorable distribution of the rainfall. In 1924 the rainfall was 50 percent less than that of 1922; but because of favorable distribution of that fall, the yields were not reduced proportionately. In 1913 and 1914 the seasonal rainfall fell below that of 1912, but here again good distribution of the rains resulted in high yields.

So far as plants are concerned, different methods may be used to obtain economical use of water; these are: (1) reduction of the number of plants to the acre, as is demonstrated by Nature in arid regions, where there are few plants to a given area; (2) growing smaller or dwarf varieties, as Dwarf milo, dwarf sorghums, and smaller varieties of smaller cereals; and (3) pruning and cutting, as in treetops, which should be kept small, particularly when the trees become older and larger. When a serious shortage of water threatens, perennial forage crops may be safeguarded against drought by cutting them, in order to reduce leaf surface and hence transpiration.

The planting of small grains may be so timed as to enable the plants to escape drought by allowing maximum growth during the periods of most precipitation and of least evaporation.

Soil factors. Usually, in semiarid regions the undisturbed subsoils must mainly be depended upon for the production of crops, although sometimes when rains are frequent and not very heavy, the topsoils may be more important in supplying water. Owing to the fact that deep tillage does not pay in dry farming, ordinary depth of tillage is an important factor not only in preparation of the seed bed, but also in destroying weeds and in water conservation.

Plowing. A large number of tests have established the fact that ordinary plowing to depths of from 6 to 8 inches gives best results in dry farming. Yields cannot be increased nor can the effects of drought be mitigated by plowing any deeper (Ch. 11).

Summer-fallowing. Summer-fallowing during alternate years is commonly practiced in dry farming, primarily to store moisture during one season for use during the next. At the North Platte Experiment Station, Nebr., Burr (1914) has reported that as much as 33 percent of the precipitation of one season may, under favorable conditions, be carried over to the next, and that only about 10 percent under least favorable conditions may be carried over.

When summer-fallowing is practiced, one half of the cultivated land is cropped, commonly with wheat, while the other half is fallowed. In summer-fallowing, destruction of weeds is very important in the conservation of water. Other objectives attained in summer-fallowing are the accumulation of available plant nutrients (particularly nitrates) and the preparation of an excellent seed bed for fall-sown wheat.

In summer-fallowing, plowing is commonly done in the fall and early spring, and subsequent cultivation during the summer is rather shallow, consisting of "duck-footing," "roding," and "slicking" at intervals to undercut weeds and maintain a soil mulch (Figs. 58 and 59). At most dry-farming experiment stations in the Great Plains region, late spring and early summer plowing followed by clean after-tillage has proved to be the most economical and productive practice.

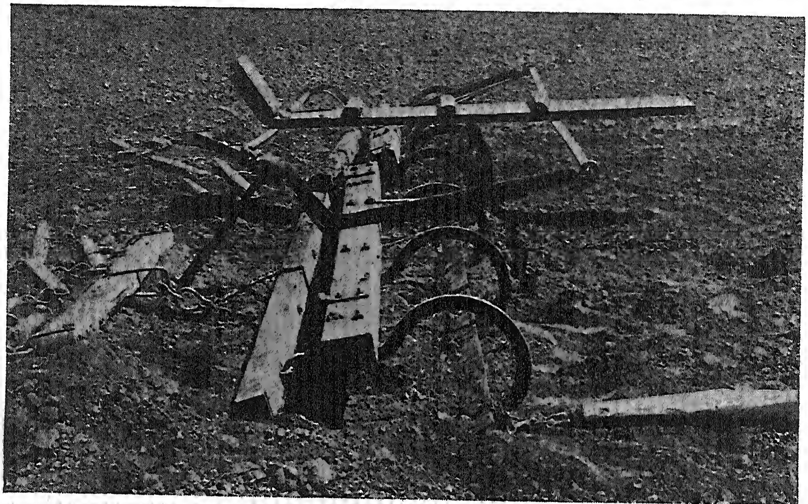

Fig. 58. A gooseneck slicker commonly used in summer-fallowing and weeding in the wheat-growing region of northwest United States. (U. S. Dept. Agr.)

According to Chilcott (1931), experimental results would indicate that there is no reason why, except possibly on heavy soils, the moldboard plow should be used in dry farming, because other implements like the duck-foot type of cultivator can be used more economically and profitably (Fig. 59).

Listing in dry farming. Early tillage after harvest is usually a good practice, particularly in seasons when there is sufficient water to favor the growth of weeds. When wheat is sown on grain stubble, early listing with subsequent tillage to kill weeds has proved to be a most economical and profitable method for preparing the seed bed.

When the lister is used in preparing the seed bed for small grains, the seeding attachment is disconnected, and the implement

is used for throwing soil material into ridges with intervening furrows which catch and hold snow during winter, and enable soils to absorb more water. Listing for small grains is usually done in the fall for spring planting, when the ridges are either "busted" with a lister or are worked down with a disk harrow or cultivator.

Listing is practiced in spring for spring-sown crops, for summer-

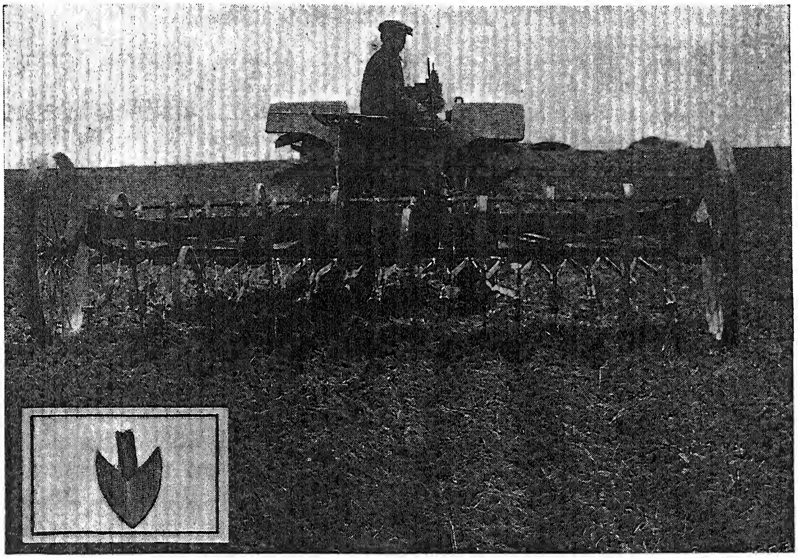

Fig. 59. A duck-foot cultivator used in summer-fallowing in northwest United States. Inset shows the shape of the cutting shares.

fallowing, and in the fall for preparing the seed bed for corn, winter wheat, and rye. Such summer-fallowed land is commonly called "listed fallow," because a lister is used instead of a moldboard plow in cultivation. Following the listing, other cultivating implements may or may not be used.

At the Colby Experiment Station, Kans., listed maize has produced higher yields than plowed and surface-planted crops. Harper (1932) has reported larger yields of wheat in the southern part of the Great Plains region (Oklahoma) from the use of a moldboard plow than from early-fall listing or one-way disking.

Crops and seasons. In dry farming and in farming in subhumid and humid regions, no simple rules can be formulated to govern the methods of tillage for all crops concerned. In many instances

the climatic conditions, and sometimes tillage methods, are favorable for wheat, oats, and barley, but unfavorable for maize, and *vice versa*. Each farmer, guided by certain fundamentals and by results obtained at the nearest experiment station, must rely on his own knowledge and the experience of others in determining the practices that are best suited to the prevailing conditions on his farm or ranch.

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REVIEW QUESTIONS

1. State the water problem in crop production, in harmony with the principle of soil fertility.
2. What are the fundamental facts regarding water in soil fertility? Why are they "fundamental"?
3. How have investigators endeavored to determine the quantity of water used in crop production? With what success?
4. Discuss the significance of the results of the water-requirement investigations.
5. What principles regarding the relationship between water requirement of crop plants and soils have been discovered? Why are they called "principles"?
6. What is the difference in the problems of controlling soil water in humid and subhumid regions?
7. How may the water-control problems be met in humid regions? In subhumid regions? In dry farming?
8. What significance has the fact that eastern Nebraska has a 50-bushel climate?

CHAPTER 13

IRRIGATION AND LAND DRAINAGE

Archeology of prehistoric peoples indicates that irrigation, or the application of water to lands by artificial methods, is a very old practice. One of the oldest written records that refers to this ancient practice is found in Genesis 2:10, which is: "And a river went out of Eden to water the garden. . . ." Evidence points to Egypt as its place of origin. Ancient Egyptian paintings and sculptures show that water was baled up for watering crops at least 4,000 years ago (Ch. 1).

According to Mead (1929), Hammurabi (2067-2025 B.C.), probably the most illustrious ruler of ancient Babylon, promulgated a code of laws relating to irrigation. On a clay cylinder he wrote his views of the importance of irrigation in the economic life of that people, as follows:

> I have made water flow in dry channels and have given an unfailing supply to the people. I have changed desert plains into well-watered land. I have given them fertility and plenty and made them the abode of happiness.

The valley of the Nile constituted the main granary of the Roman Empire, principally on account of natural irrigation. Ancient as the practice of irrigation was in Egypt, it was not scientifically used until after British occupation in 1882.

Traces of crude irrigation systems of the prehistoric peoples are to be found in southwestern United States. Records show that in the Rio Grande Valley, N. Mex., early Spanish explorers replenished their food supplies from the irrigated crops of Pueblo Indians. Later the crude Indian methods were improved by the Spanish conquerors and their descendants.

Modern irrigation was begun in the United States in 1847, by the pioneers of Salt Lake Valley, Utah. Since that time the practice has spread, first into the richer and warmer valleys and then generally throughout the arid parts of the West and elsewhere,

until now there is an area of about 20,000,000 acres under irrigation in continental United States (Figs. 60 and 61).

Primitive methods of lifting water. Baling up water by hand, which is obviously the most primitive irrigation method, is still practiced by primitive people in many places. The first step in improvement over hand-baling consisted in raising water by means of a bucket, counterbalanced, attached to the end of a long pole

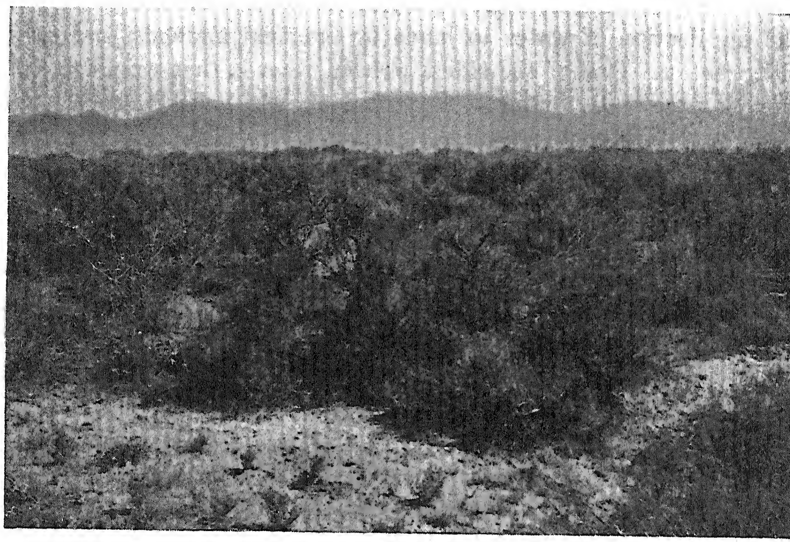

Fig. 60. Sagebrush desert, Minidoka project, Idaho. (See Fig. 61 for results of reclamation.) (Bur. Reclamation, Dept. Int.)

commonly pivoted to the top of a tall post, called "shadoof" in Egypt and "denkli" or "paecottah" in India. The water-wheel, known as "sakia" in Egypt and "harat" or "Persian wheel" in northern India, is another ancient aid to irrigation. Of all ancient irrigation implements, the screw, which was invented by Archimedes about 200 B.C., is probably the most ingenious. The shadoof, the sakia, and the screw are still in use.

Modern methods of pumping. Human beings and animals were not relieved of the irksome task of lifting irrigation water until after Watt had improved the steam engine in 1763, when steam pumps came into use. Pumps (steam and electrical) for irrigation range from small ones for a few acres up to huge power plants for extensive acreage.

Lifting water by permanent works. Very early ancient people saw that they could divert the water from a stream at a point higher up and direct it through channels to the land they wished to irrigate. They also learned how to raise the water in a stream or channel by obstructing its flow, to cause the water to flow directly onto the land, into the irrigation channels, and from the irrigation channels into the fields. Thus originated the ideas of

Fig. 61. Irrigating potatoes where sagebrush formerly grew. Minidoka project, Idaho. (Bur. Reclamation, Dept. Int.)

permanent canals and weirs, or barrages, for lifting irrigation water.

Canals must be constructed to give some slope to the water to make it flow, and the gradient may be less than that of the water in the stream. Thus it is possible, without pumping, to irrigate an area that lies at an elevation higher than a point opposite on a stream, by diverting the water at a point higher upstream and, by gravity, conducting it down to the area by means of a canal.

Weirs are structures built across streams to produce higher levels of water on the upstream side to enable it to flow easily into canals that lead off from the streams. An artificial upstream level may be produced by shutting the doors or gates of the weir provided. Usually, in such a manner, upstream levels are increased by from 10 to 14 feet.

Reservoirs to assure water supply. Credit must be given early ancient people for conceiving the idea of storing water for irrigation purposes against times when wells and streams ran low. Irrigation reservoirs came into use at a very early date, as remains of ancient reservoirs throughout the world indicate. The first form probably consisted of earth-embanked basins which eventually had to be abandoned for new ones on account of their filling up with silt and mud.

Since the building of the Periyar Dam in southeastern India, completed in 1897, the problem of keeping similar resorvoirs clear of silt has been solved. This dam is provided with sufficient sluiceway near its base to allow all flood water with its load of alluvium to pass; then the later clear water is stored. The Aswan Dam in Egypt (originally completed in 1902) is probably the best example of modern construction that meets the silting problem: its construction is such that a perpetual life for the reservoir is practically assured.

Water suitable for irrigation. Water for irrigation should be free from appreciable quantities of salt. Although all fresh water contains small quantities of salts, crop plants can tolerate much larger concentrations when good drainage is provided. In some places both soils and crops have been ruined by accumulations of salts carried by irrigation waters; also by silt on clay soils.

Salts in irrigation water affect not only the crop plants, but likewise the soils, as several investigators have shown. In some places gypsum is added to and applied with irrigation water with a view to improving the permeability of "tight" or heavy-clay subsoils. Metzger (1929) and Bartholomew (1931), in their studies of rice soils, found that continual irrigation with calcareous waters increased the quantity of calcium, particularly in the topsoils (Ch. 4).

Drainage with irrigation. For successful and permanent irrigation, drainage of the soils is a necessary concomitant. In only a few places is artificial drainage unnecessary. After many years of experience, engineers have learned that the supply of irrigation water is not the only problem, but that drainage is fully as important to assure continued productivity.

History of irrigation shows that in some places lands, formerly productive through irrigation, are now abandoned, whereas in other places lands have been successfully irrigated for centuries.

Abandonment of irrigated lands is commonly related to quality of irrigation water and land drainage.

According to Scofield (1927), if irrigation waters contain appreciable quantities of salts like those of sodium, a faulty system of irrigation is almost certain to result in failure. It is not safe to use such water sparingly. Salt brought in by irrigation water should not be allowed to accumulate in the root zone, but enough water should be used to leach the root zone from time to time. The greater the salt content of the irrigation water, the more frequently it is necessary to leach the soils. If conditions of the subsoils and substrata do not allow removal of these salts, artificial drainage outlets must be provided. Thus, with the same irrigation water, it is possible for one farmer to make desert land a permanently productive garden by providing artificial drainage, while another may make it a barren waste.

Forms of irrigation. There are two major forms or systems of irrigation: namely, (1) basin and (2) perennial. In addition, there are a number of minor systems like (a) water meadow, (b) warping, and (c) sewage farming, depending on the object in view.

The basin system is ancient (Fig. 63). It consists of an area surrounded by embankments or borders to form a pool when water is applied until depths of from about 2.5 feet to 4 or more feet are attained. After a time the water is run off, and the land is then planted with crops. No further watering is required to grow them to maturity. In Egypt some of the basins are very large, some containing as many as 50,000 acres.

This system originated in the fact that rivers usually could be made to supply water once a year during flood flow, and that the production of food crops followed the flood period, as in the valley of the Nile.

Perennial systems of irrigation consist of canals which provide constant or perennial supplies of water. In this system branch canals lead off from the main canal, and smaller branches lead off from the main branches, and so on down to small trenches or runlets. The first change from the basin to the perennial system in Egypt was made during 1898-1902; the perennial system was introduced in order to meet the water requirement of sugarcane which the Khedive (Ismail) wanted to grow on a large scale.

Water meadows had their origin in Roman times. This system of irrigation is practiced in the coldest and wettest months of the

year, in order to stimulate grass and meadow herbage. It also protects the grass from frost, as the water used is usually warmer than the natural ground water. Examples of this form of irrigation may be found along the Avon and Churn Rivers in England.

Warping is a basin form of irrigation, but differs in that suspended materials (locally called "warp") are added to the land, forming a new soil surface. Warping is confined almost exclusively to lands lying below tide mark along estuaries or tidal rivers. Along the Trent, Humber, and Ouse Rivers, England, provision has been made for allowing the muddy tide waters, at stated times, to spread over wide areas. The suspended materials settle out as mud, and the clear waters return to the rivers with the falling tide.

Sewage irrigation, practiced in the vicinity of inland cities and towns, is accomplished by passing the sewage through modern settling-tank systems, and the effluent, which is rich in nitrogenous matter, is used to irrigate cultivable lands. It is said that the drainage from Cairo, Egypt, is much more effective than the silty water of the Nile for irrigation.

Distribution and volume of water. Distribution of irrigation water is determined by the kind of crop and by the cropping system. Some crops require water oftener than others, and much depends on the temperature at the time of irrigation. To keep sugarcane, indigo, and cotton alive during summer before the monsoon begins in India and before the Nile rises in Egypt, water is applied at intervals of about 15 or 20 days. Paddy rice requires practically a constant supply of water. In northern India excellent crops of wheat can be produced during the winter months by only two or three waterings.

The quantity of water used in a single irrigation varies widely. Under a perennial system, from 2 to 5½ acre-inches may be applied, whereas under the basin system, 26 or more acre-inches. The quantity of water soils can retain when in need of water varies from the equivalent of ½ acre-inch per foot depth of sand to about 2¼ acre-inches per foot of clay loam (pp. 34 and 35).

Duty of water means the quantity of water required per acre for irrigation. This is usually expressed in terms of acre-inches or acre-feet. Duty of water varies with quality of water, supply, purpose in view, temperature, climate, season, soil, drainage, slope of land, and crop. In a given locality, it may be necessary to apply water more frequently to alkali than to nonalkali soils. The quan-

tity of water delivered during a season varies from 1.25 acre-feet, in places that have 12 inches of effective rainfall during the growing season, to 3.5 or more acre-feet in arid regions that have long cropping periods and high temperature. Because of the various factors involved, no hard and fast general rules can be formulated to govern the quantity of water used. However, data are given to illustrate duty of water.

Under Utah conditions, Brossard (1920) has given the following data on quantities of water that should be used for irrigation purposes:

Wheat on fertile, well-tilled soils requires 7.5 acre-inches in 2 waterings.

Wheat on shallow, gravelly soils needs as much as 18 inches in 4 or 5 waterings.

Oats and barley require about as much water as wheat.

Rye needs somewhat less water than other small grains.

Maize requires from 12 to 18 acre-inches, commonly in 2 irrigations.

Alfalfa can use from 12 to 24 inches, depending on age of crop and depth of soil, in 3 or more waterings.

Pastures and meadows require from 12 to 24 inches.

Sugar beets, potatoes, carrots, and similar crops require from 15 to 24 acre-inches of water, commonly in 3 or more waterings.

Parshall (1927) has given the following data for average conditions in Colorado:

Crops	Acre Yields	Acre-feet of Water
Alfalfa	2.25 to 4 tons	1.5 to 2.5
Sugar beets	10 to 15 tons	1.5 to 2.0
Small grains	30 to 40 bu.	1.0 to 1.5
Potatoes	200 to 250 bu.	1.0 to 2.0
Beans	20 to 25 bu.	0.5 to 1.0

When to irrigate. The effective use of water, one of the most important problems in irrigation farming, depends on several factors, the principal one being the time of application, particularly in relation to stage of plant growth. A few facts may be of interest to illustrate this point.

Widtsoe (1914) has suggested that wheat and other small grains, peas, beans, and other short-season crops, after being planted on soils well supplied with moisture, should be allowed to grow as long as possible without watering, to develop normal root systems.

Some crops have *critical periods* in relation to water supply. For wheat the critical period is about heading stage. Kezer and

Robertson (1927) found that water applied to wheat at the jointing stage (2 joints) increased the yield of both grain and straw; and that when it was applied at heading stage, the yield was somewhat less, but the quality was better. Watering before heading seems to be the best time for oats and rye. Barley and vegetables need sufficient moisture throughout the growing period.

Potatoes respond best to regular irrigation of about 1 acre-inch weekly. When the crop is irrigated but once, the best time to water is when the plants are in full bloom or when tubers begin to form.

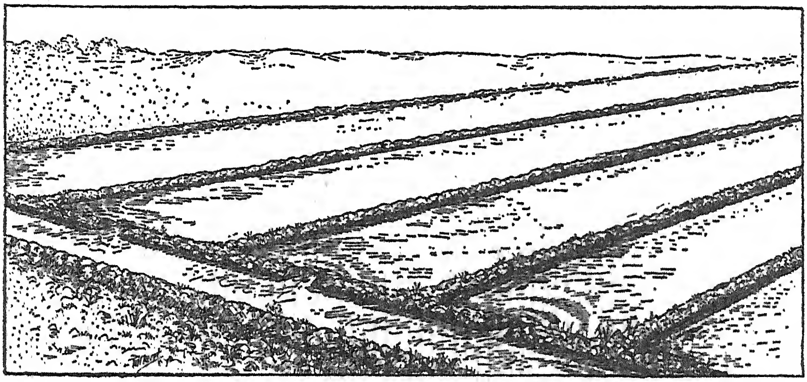

Fig. 62. Border method of irrigation.

Open soils are best suited for irrigation; heavy soils under irrigation decline rapidly. In arid and semiarid regions, where water supply is usually limited, economic crop production should probably be based on yield per acre-foot of water rather than on yield per acre.

Methods of applying water. The principal ways of applying water are (1) flooding, (2) furrow, (3) check, (4) basin, (5) border, (6) pipe, (7) overhead spray, and (8) subirrigation. The last two methods are commonly used in humid regions.

Flooding is the most common method, because it can be used on rather steep slopes and in other ways. It consists in allowing the water to run over a smooth field surface (Fig. 62). Shallow furrows or corrugations, which run up and down the slope, may so direct the water as to irrigate the whole field. The furrows that conduct the water usually follow grades, and may extend in more or

less curved lines over the land. Alfalfa, small grains, hay, Indian corn, and orchards are commonly irrigated by this method.

The furrow method, as the name indicates, consists in applying water in furrows. This method of irrigation is very commonly used for crops that are planted in rows, including orchard trees and small fruits (Fig. 61).

The check method consists in pooling water successively into

Fig. 63. Irrigating an orchard in California by the basin method.

checks or rather large squares into which fields may be divided. Each check is surrounded by low, flat levees and is bordered by a supply ditch. Alfalfa is commonly irrigated this way.

The basin method is similar to the check method, but differs in that the basins are smaller and the method is commonly used in orchards, particularly in California, Texas, Arizona, and New Mexico during winter months when water is abundant (Fig. 63).

The border method is flood irrigation between controlling borders or ridges. An area is laid out into strips, lands, or beds which usually extend in the direction of the steepest slope. Water is turned into the upper end of each strip, and it moves down the slope as a thin sheet, several strips being supplied with water from a common ditch or lateral. Usually a field is divided into bands or borders each of which is watered separately (Fig. 62).

The pipe method is used in places where water is pumped from wells and where it is conducted from canals under pressure. The main feed pipe is laid underground across the top of the area to be watered. From this main the water is obtained through standpipes which are placed at regular intervals. This method may be used in orchards when other methods will not operate on account of uneven or unfavorable surface relief. It is also used on small areas such as lawns through the use of porous hose and small underground pipes.

The overhead-spray method consists in applying water to crops under pressure by means of pipes which spray it into the air and let it fall as rain (Fig. 38). This system may be used for any crop that has sufficient value to justify the cost. Vegetable growers find this method especially useful in preparing soils for transplanting and in supplying quick-growing crops with adequate water. Sprinkling irrigation is also used in deciduous and citrous orchards and for lawns and golf greens. A system of overhead irrigation commonly used is that devised by Skinner in 1896.

Subirrigation, or the application of irrigation water below the surface, is accomplished by means of open drainage ditches and underground drains. Obviously, this method requires peculiar underground conditions to be successful—for example, lands with shallow and open topsoils underlain by impervious or saturated subsoils.

In places, subirrigation is practiced by means of drainage systems. Devices are constructed for controlling or checking the flow of water in the ditches and drains during dry periods. Drainage systems for lands on which intensive crops are grown should be so designed as to provide subirrigation if necessary.

Irrigation in humid regions. Although irrigation is practiced principally in arid and semiarid regions, it is also used to supplement precipitation in humid and subhumid regions in order to carry crops through periods of minor and major droughts which may occur in places where the average annual precipitation is ordinarily sufficient for the production of satisfactory crops. In humid and subhumid regions, irrigation is usually done by sprinkling, surface irrigation, subirrigation, and porous hose pipes. A reliable source of water during critical periods of crop growth is very important; also in the successful production of vegetables.

Reclamation service. Up to 1920, 70 percent of the acreage reclaimed through irrigation in the United States was to be credited to individuals, groups of farmers, and co-operative companies. But with the lack of adequate administrative control over streams and water rights, much litigation resulted.

Colorado was the first State to assume administrative public control of streams. And later (1902), after favorable locations

Fig. 64. Hoover Dam and Lake Mead formed by it. Completed in 1935 by the U. S. Bureau of Reclamation. Total cost, $114,000,000. It is 726 feet high, and 650 feet thick at its base. It provides water for about 1,000,000 acres, supplements the water supply for nearly 3,000,000 people, provides power, and controls floods of the Colorado River. (Bur. Rec.)

had become exhausted through developments of individual and co-operative irrigation projects, Congress passed the Reclamation Act by which the Federal Government became active in reclamation, working in co-operation with commercial and district organizations to provide funds for building reservoirs, to regulate rivers, and to construct long and costly canals.

Through the Federal Reclamation Service, several huge dams have been built, among which are the Shoshone Dam in Wyoming; Roosevelt Dam on the Salt River project in Arizona; Arrowrock Dam on the Boise River, Idaho; Elephant Butte Dam on the Rio

Grande, N. Mex.; and the Pathfinder Dam of the North Platte project in Wyoming. Dams of other irrigation projects include the Coolidge Dam on the Gila River, Ariz., completed in 1928; the 417-foot-high Owyhee Dam on the river of the same name in the eastern part of Oregon, completed in 1932; and the 726-foot-high Hoover Dam on the Colorado River between Arizona and Nevada, completed in 1935 (Fig. 64). The Hoover Dam is regarded as one of the greatest engineering works of this age.

It has been estimated that the possibilities of irrigated agriculture in the United States include 63,000,000 acres, or about 100,000 square miles.

LAND DRAINAGE

The draining of lands consists in removing surplus ground or surface water, or both, usually by such artificial means as surface-runs, open ditches, and underground drains. A successful drainage system may include all three methods.

Harmful effects of too much water. Excess water in soils is a source of many evils, not only to crops, but to animals as well. Too much water makes tillage more arduous and it delays planting, and because of it the best time of planting may be missed altogether. As a result of avoiding wet places in cultivation, fields become irregular, and many farms have become badly "cut up."

Inasmuch as crop plants require mediums in which their roots can develop normally, soils must be well drained to allow aëration, to enable them to warm up, and allow root development (Fig. 65). Water of saturation proves to be harmful, because it excludes air, retards conduction of heat, and prevents the roots of crop plants from penetrating to lower depths.

Benefits of drainage. Removing surplus or stagnant water from farm lands by deep drainage, as with tile, results in many benefits, among which may be mentioned the following: It improves tillage and planting conditions, allows soil aëration, enlarges the root zone of plants (Fig. 65), increases the supply of available or beneficial moisture by enlarging the root zone, increases the supply of available plant nutrients, improves the physical condition of soil material, increases certain types of chemical action, favors development of beneficial soil micro-organisms, and improves health conditions for farm animals. Drainage of some swamp and marsh areas improves conditions for public health. Other areas should be left

for needed wildlife refuges. In irrigation and management of alkali soils, good drainage is essential in removing injurious salts.

Basic facts. Artificial drainage concerns ground water primarily (p. 31), which is also called *phreatic water* (Greek, meaning well).

Fig. 65. A high water table at planting time results in limited root growth near the surface. When the water table lowers during a summer dry period, the plants suffer for want of water (illustration to left). Right—Proper drainage causes deeper rooting and assures a better supply of available water. (After Haswell.)

The upper limits of the ground water, or the *phreatic surface,* on low wet lands may be the ground surface. Water that enters underground drains is phreatic, or free, water. Hence tile drains do not draw any water that is held in the capillary fringe which extends to varying height above the phreatic surface in the zone of aëration (p. 32). Between parallel underground drains, the water table may

be higher than the drains, because above the drains the surface tension of the capillary water is reduced by drainage (Fig. 66).

Essentials of land drainage. In land drainage, the first essential consists of proper outlets for removal of the water. The next important step is to determine the lines of the mains or receiving drains which must occupy the lowest part of natural hollows, if there are such; and the third, to determine the direction of the

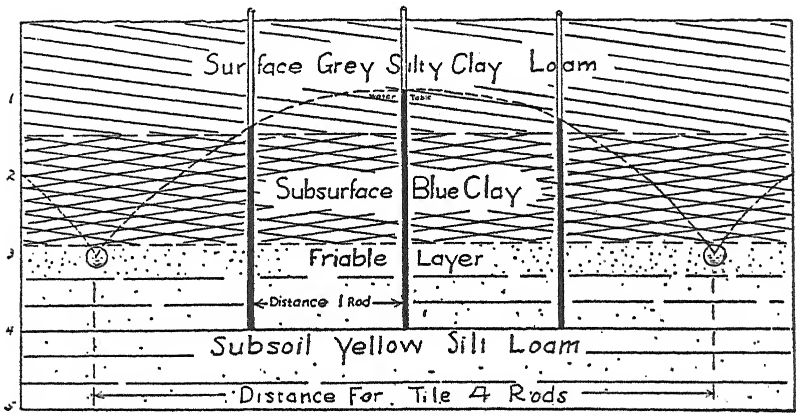

Fig. 66. Tile placement and relation of ground-water table to lines of tile. The higher water level between the lines of tile is caused by capillarity. (After Powers.)

parallel drains that must run in the lines of the greatest slope of the ground. On flat areas, fall or grade lines are obtained by increasing the depth of the drains at their lowest ends.

Surface drainage. On many flat fields, surface drainage may be effected by plowing the land into ridges or in narrow "lands" up and down the gentle slopes to allow the water to run into intervening furrows, and thence down the furrows into ditches. Plowing heavy soils into ridges to facilitate surface drainage was practiced in ancient times.

Permanent surface-runs, or shallow runways for water, are commonly advisable. They are usually about 1 or 1.5 feet deep and 10 feet wide, and are used to remove surface water during heavy rains and melting snows. They may also be used to protect depressions, and to divert surface waters and thus prevent their flowing onto low areas. For protection against erosion, these "runs" should

be kept permanently sodded. Their shallow depth makes possible easy crossing of them with farm vehicles and implements.

Open ditches. For many centuries the only method used in freeing land of surplus water was the use of surface drains and open ditches. Open ditches are still necessary in modern drainage. They may vary in size from about 3 to 5 feet deep to large canals.

To be effective, open ditches must be constructed at intervals of 4 or 8 rods, depending on kind of soil and conditions for drainage. But there are many objections to open ditches. They must necessarily occupy much land, they cut fields into irregular and inconvenient shapes, necessitate the building of many farm bridges, harbor noxious weeds, they are expensive to maintain, are constant sources of danger to livestock, and they afford breeding places for injurious and disagreeable insects. Covered drains like those of tile have proved to be most effective and economical.

Under certain conditions, however, small open ditches may be useful—for example, as temporary outlets for a tile system until the bed of a stream may be lowered by dredging.

In large marshes and swamps where much water has to be removed and where fall is slight, large dredged ditches usually serve as outlets. Often these large ditches are constructed by straightening and deepening water courses.

Underground drains: historical. Covered drains made by burying stones and bundles of faggots in trenches were known to the Romans in Cato's time. No doubt this art was preserved during the Dark Ages, to be revived centuries later. In the middle of the seventeenth century, Blith (Eng.) advocated drainage by means of trenches partly filled with either stones or faggots. Later, bricks were placed in the bottom of the trenches. Blith's teachings, however, were little regarded.

In the last half of the eighteenth century, Elkington, an English farmer, devised the "sink-hole" method of draining sloping lands that were made wet by seepage and springs. He cut deep drains through the impervious substrata to tap the underlying bed of sand or gravel in which the water was pent up by the impervious overlying strata. When necessary he assisted drainage by "wells" or sugar holes. The released water was conveyed in covered drains to the nearest ditch or stream. Under proper conditions this system proved to be successful, and attracted wide attention.

Near the close of the eighteenth century, the mole plow was

invented, which consisted essentially of a pointed cylinder held to a plow beam by a strong, narrow bar. When this cylinder was drawn through soils it made small tunnels at depths of from 15 to 18 inches, which served to carry off the water. These mole drains were not permanent, because in time they would become clogged or filled with silt. Inasmuch as this method was economical and successful, though only temporarily, it obviated the digging of so many trenches.

Tile drains. The principles of land drainage were not established until 1823, when Smith of Deanston, Perthshire, Scotland, rediscovered the principles of drainage that were indicated by Blith about 175 years before. Smith demonstrated and expounded these principles so effectively as to bring to pass not only a revolution in the art of land drainage, but also an era of agricultural progress (Ch. 1).

Smith's system consisted in providing every field that needed drainage with parallel underdrains (30-inch trenches filled to a depth of 12 inches with 3-inch stones), running in the line of the greatest slope of the land, and discharging into main drains constructed along the lowest part of the fields, with subdrains in subordinate hollows. The parallel drains were near enough to each other (from 10 to 40 feet) to carry off all rain water that would fall at any time upon a drained area. Parkes, engineer to the Royal Agricultural Society, advocated a greater distance between parallel drains, and a depth of at least 4 feet.

The great labor and cost involved in constructing the stone underdrains led to the use of burnt earthenware soles and horseshoe tile. But these, too, proved to be expensive. Later the inventions of tile-making machines, cylindrical tile, and trenching machines stimulated agricultural improvement through land drainage.

The first recorded use of tile for underground drainage in the United States was on a farm near Geneva in New York State, where a system of tile drainage installed in 1835 is still operating successfully.

Constructing tile drains. All drains should be laid out and constructed in accord with a plan of the whole drainage system. Whether it be the main outlet ditch, tile main, submain, or laterals, construction should begin at the lower end. With tile drains, the tile should be placed end to end with joints fitting closely at the

top. Grade lines for the tile are so made as to give slope to allow the water to run toward the outlet (Fig. 67).

The depth at which to lay lines of tile in parallel drains may vary according to conditions. In clay soils, 3 feet is a common depth; in sandy soils, 4.5 feet; in peat and muck soils, the tile should be laid at a depth of 4.5 or more feet, to allow for settling of the soil mass.

Distance required between parallel drains is determined mainly by subsoil conditions. It may vary from 33 feet in "springy"

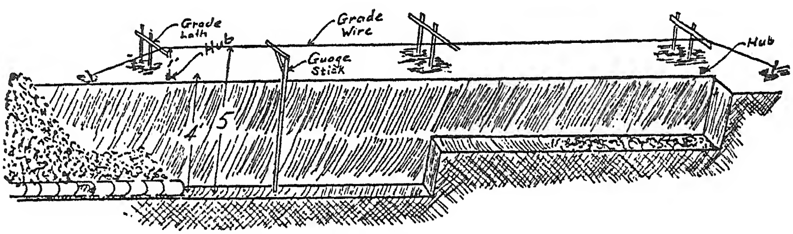

Fig. 67. Method of laying tile to grade. The tile are laid end to end on a sloping grade line to allow the water to run toward the outlet. (After Powers.)

areas and heavy soils to 132 and more feet in soils that have open or porous subsoils. Sixty-six feet (4 rd.) is a common distance in loams, silt loams, muck soils, and peat soils. From 80 to 100 feet may prove to be adequate to properly drain loams and silt loams. Under similar conditions, the distance between lines of tile or drains may be increased with drain depth. The ratio of distance to depth, however, varies with different types of soils.

The size of tile to use in drainage varies, depending on fall and quantity of water to be carried. For parallel drains, 4-inch tile is common. The sizes for submains and mains are much larger, being determined by fall and quantity of water to be removed.

Covering. Soon after tile are laid, sufficient soil material should be shoveled into the trench to cover them and to hold them in place until the trench is filled. The loose soil material should be packed around the tile and lightly tamped above it. Covering and anchoring tile in this manner is called "blinding" (Fig. 67). Trenches may be filled by hand labor or by the use of plows and scrapers.

Outlets of tile drains should be well protected and made permanent (Fig. 68).

How tile drains work. Free or gravitational water flows into tile drains through the joints between the ends of the tile. In case of porous tile, about 95 percent of the drainage water enters the tile in this manner, about 5 percent entering by soaking through the walls.

Tile drains do not have any peculiar power to draw water from the supply (available) that plants use. They remove only the free water (p. 32). If on lowering of the water table, tile should

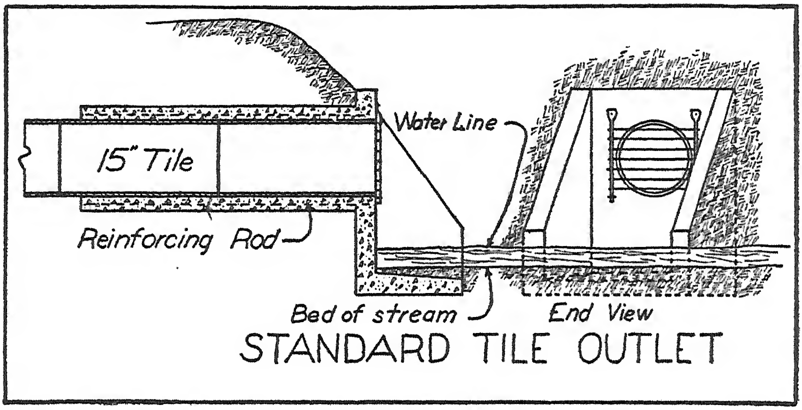

Fig. 68. Outlets of tile drains should be well protected and made permanent. (After Powers.)

draw water from the capillary fringe, it would be because tile attraction for water would be greater than soil attraction.

Where to lay lines of tile. The location of tile drains is determined by the object in view, which is to remove surplus water. Springs may be tapped directly. A line of tile laid through the center of a wet "draw" usually proves to be effective. On wet flat areas, the location of parallel drains is usually determined by the slope of the land and the distance between drains. In removing damaging seepage water (on slopes) the lines of tile should be laid at sufficient distance on the higher side above the wet areas, and deep enough, to catch the underground water before it is allowed to seep out on the land below (Fig. 69, A).

Systems of tile drainage. A system of tile drainage means the arrangement of lines of tile designed to drain an area of wet land. Usually it consists of parallel drains or laterals (single drains into which no other line empties), submains, and mains.

Lines of tile may be arranged in different ways, as determined by natural conditions, surface relief, and area to be drained. Six systems are recognized: *natural* or random, *gridiron, herringbone, intercepting, double-main,* and *grouping* system. (Fig. 69.)

Vertical drains. Potholes, or depressions that have no natural surface drainage, constitute special drainage problems. Drainage of such a depression may be effected by cutting a trench through the lowest point in the surrounding ridge and, if conditions are

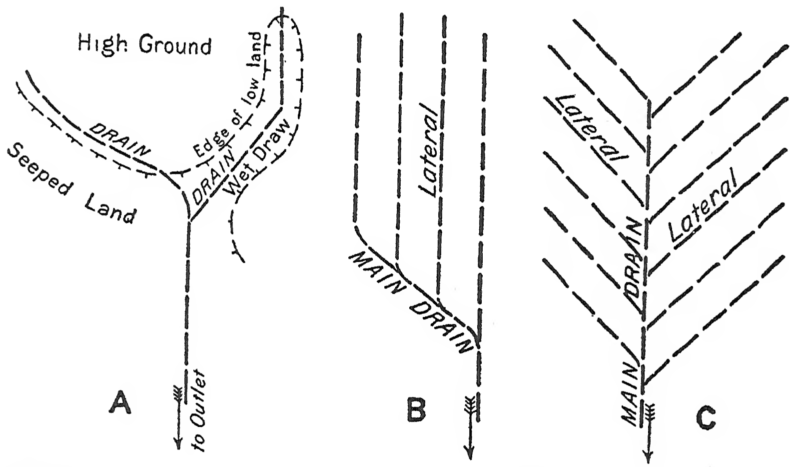

Fig. 69. Three principal systems of tile drainage: A, natural or random; B, gridiron; and C, herringbone. (After Haswell.)

right, by a vertical drain which may conduct the standing water down through a tight substratum into dry and more open or porous material below.

Arterial drainage. Rivers, which in all countries are the natural systems of arterial drainage, are commonly supplemented by artificial means to prevent water-logging and flooding of lands in low-lying districts. State and national governments co-operate in the improvement of rivers, construction of dikes and levees, and in the establishment of flood-water basins for the prevention of floods.

The subject of arterial drainage overlaps that of land reclamation.

Land reclamation. Land reclamation by drainage includes (1) recovery of land from seas, lakes, and rivers, and (2) improve-

ment of marsh, fen, and swamp lands for agricultural and other purposes. The drainage of many such areas requires pumping. In the United States, in 1930, there were about 1,512,000 acres, or nearly 2,400 square miles in organized land-drainage enterprises partly or wholly dependent on pumping for removal of drainage waters.

The greatest work of reclamation by drainage is the embanking and draining of the Zuider Zee in Holland. This extensive project includes a large dam, more than 18 miles long (29.3 km), which separates this inland sea from the North Sea. The reclaimed land consists of 4 "polders," or drainage units, aggregating about 556,000 acres (225,000 hectares, or 870 sq. miles).

In the United States, co-operative reclamation began in 1850, when Congress passed the Swamp Act which provides for the granting of wet lands to the States in which they lay, with the understanding that the States are to drain and sell them. The real era of land drainage began in 1885, when the dipper dredge was invented. In the reclamation work, the States have provided for district enterprises. Much of the prairie lands of the Mississippi Valley have been drained, over 8,000,000 acres being reclaimed in each of the States of Minnesota, Michigan, Indiana, and Ohio. In the States, 84,408,000 acres (131,900 sq. miles) have been drained in organized efforts, and several millions more by individuals.

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REVIEW QUESTIONS

1. What are irrigation and land drainage? When discovered?
2. How can land, through irrigation, become unfit for agricultural use?
3. What are some of the conditions of land and crops that necessitate different systems or methods of irrigation? Give examples.
4. What determines the distribution and volume of irrigation water? Explain.

5. Compare the effects of irrigation when, through the basin system, the water used deposits silt that is brought down from a region of fertile, undeteriorated lands, as compared with water that deposits silt from badly eroded lands.
6. What factors determine the time to irrigate crops? Explain.
7. Explain how draining lands increases available water for crops. State some basic facts that pertain to land drainage.
8. What are some of the essentials of land drainage? Describe surface drainage. Underground drainage.
9. Explain the necessity of different systems of tile drainage. Give examples.
10. Discuss the vital relationship between a watershed where people depend on huge storage reservoirs for regulation of stream flow (such as the Rio Grande Valley) and usable water.
11. Name some important irrigation projects that have been proposed or developed since the building of Hoover Dam.
12. Discuss some of the important factors in the management of watersheds of arid and semiarid regions as compared with those of humid regions.
13. What has been the effect of drainage of certain swamp or marshy areas on wildlife?
14. Make a sketch showing the Salt River Watershed, Arizona, Roosevelt Dam, Roosevelt Reservoir, and the lands on which the impounded water is used for irrigation.

CHAPTER 14

SOIL AËRATION AND SOIL FERTILITY

Crop plants grow poorly or perish on soils that are too compact or are saturated with water, principally for the want of oxygen in the soil mediums. Nevertheless, it is possible to grow plants to maturity in water cultures in which the roots are continuously submerged, but only when the culture solutions are aërated or frequently changed.

Some plants are more sensitive than others to a deficiency or lack of soil air. Plants like maize, cotton, potatoes, small grains, clovers, alfalfa, and sugar beets, which require well-aërated soils, soon turn yellow and wilt when soils become submerged; and if the saturated condition remains for a long period, they ultimately die. To be sure, other factors, such as denitrification and accumulation of toxic substances, will affect plant growth under these unfavorable conditions, but indirectly, the primary cause is exclusion of air.

Potatoes are peculiarly sensitive to a deficiency of soil air. This crop requires soil air almost as much as it needs water, because the roots and tubers respire freely and need oxygen for the maintenance of normal disease-resisting power. Hence the high quality of tubers that are produced on well-aërated soils (sandy), and the care that must be exercised in irrigating this crop. Legumes also have high aëration requirements.

Livingstone and Free (1917) have found that different plants differ greatly in their need of soil air, as was indicated by the resulting death of certain plants and the continued growth of others when oxygen was replaced by nitrogen.

It is interesting to note that when soils are wet and the water table is near the surface, plants develop shallow roots, as the result of the exclusion of air. Bog plants and those which grow under submerged conditions have air spaces in their organs, which supply the roots and rhizomes with oxygen.

Trees that grow in bogs, swamps, and on saturated soils are

shallow rooted, some having no taproots, like the larches, or tamaracks (*Larix laricina*). Some trees develop what are supposed to be organs for aëration—cypress "knees," for example.

Soil aëration and roots. Exclusion of air affects plant roots directly in two ways: (1) by depriving them of oxygen that is necessary in respiration of the protoplasm of the root cells; and (2) by injury consequent to accumulation of toxic substances.

It is known that oxidation or respiration is closely associated with the metabolic activities of plant roots; hence whatever decreases oxidation by roots also decreases plant growth. Roots grow toward a greater oxygen supply as well as toward more moisture.

Oxygen is particularly important in the development of root hairs. In a moist, well-aërated soil, root hairs on a given plant develop abundantly; in a wet soil comparatively few develop; and in a saturated soil very few or none develop (Fig. 29).

In a well-drained soil root development, absorption of water by roots, and the processes that are concerned in soil fertility take place under oxidizing conditions, as contrasted with a reducing condition when a soil becomes saturated or submerged.

Toxicity to roots caused by accumulated carbon dioxide has been established. Free (1917) and Stiles and Jorgensen (1917) observed that when air, oxygen, and nitrogen were blown through culture solutions growing buckwheat and barley, normal growth was obtained; but that when carbon dioxide was blown through, the plants soon died.

Furthermore, oxidation by roots is an important factor in absorption of water. Excluding oxygen, therefore, destroys the absorbing power of roots, because oxidation ceases. Accumulated carbon dioxide, which seems to act as a specific root poison, causes injury by inhibiting absorption of water.

Other functions of soil air. Soil air is important in ways other than in supplying roots with oxygen, and in preventing toxicity of carbon dioxide. It is an important factor in soil productivity, since it is a vital agent affecting the activity of micro-organisms and in effecting chemical changes or reactions.

The beneficial soil micro-organisms require oxygen for the important process that they effect: namely, decomposition (decay) of organic substances, nitrification, and symbiotic and nonsymbiotic fixation of atmospheric nitrogen. Furthermore, in these processes, air is a necessary medium for exchange of gases.

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On the exclusion of soil air by excess water or otherwise, the aërobic organisms cease their activities for want of oxygen, but conditions become favorable for the activity of the anaërobic microorganisms that effect denitrification and fermentation (see Index).

Chemical reactions in submerged soils. Livingstone (1905) has found that waters from bogs usually contain certain toxic substances, and Dachnowski-Stokes (1908) has shown that toxicity of bog waters is caused neither by acidity nor lack of oxygen.

In his study of submerged soils, made with a view to obtaining further information regarding the failure of such soils to grow satisfactory crops, Robinson (1930) has pointed out that the intense reduction processes that take place under submerged conditions must be toxic to plants. His principal conclusions may be summarized as follows:

1. When organic matter was present, soil solutions under submerged conditions contained comparatively large quantities of iron, manganese, calcium, and magnesium, together with some hydrogen sulphide and other sulphides. The iron and manganese were present as acid carbonates.
2. Carbon dioxide, resulting from the action of anaërobic organisms on organic matter (in the absence of free oxygen), was principally responsible for holding iron, manganese, calcium, and magnesium in solution in submerged soils.
3. Submerged conditions caused the development, in the soil solutions, of toxic concentrations of ferrous iron, sulphides, and commonly of manganese. Toxic concentrations of ferrous iron and sulphides developed within a few days after submergence.
4. Soils that contained organic matter, on submergence, eventually produced gases—mainly methane and hydrogen in the absence of blue-green algæ, and principally nitrogen and carbon dioxide with some methane in the presence of blue-green algæ.

Rawness of subsoils. Hilgard (1892), observing normal growth of vegetables on some desert soil material that had been excavated from depths of from 7 to 10 feet, concluded that subsoils of arid regions gave no evidence of infertility known as "rawness." C. B. Lipman (1917) has observed that arid subsoils are but little, if at all, less raw than those of soils of humid regions. The rawness of some subsoil materials of humid regions is based on observations of numerous investigators in America and Europe. In his discussion of this problem, Alway (1918) has stated that the generally accepted idea regarding the rawness of subsoil materials in humid regions is not based on pot experiments nor on the growth of plants

on soil materials which had been exposed by grading operations or thrown out of excavations, but rather on observations of the growth of crop plants in certain fields in which the plow, having been run a few inches below the usual depth, had brought to the surface considerable subsoil material.

Quantity of air in soils. The quantity of air a soil contains is determined by its porosity and moisture content. The fact has been stated that, by volume, from about 40 to more than 50 percent of compact, dry material of the common soils (silt loams, loams, and fine sandy loams) is air (Ch. 2). Against the attraction of gravity, which tends to "pull" water through soils, these same materials can retain a quantity of water equivalent to from about 25 percent of their dry weights, including hygroscopic and available moisture in fine sandy loam, to about 40 or more percent in silt loam.

As both air and water must occupy the pore spaces, it is evident that in a given soil the quantity of air contained varies inversely with the quantity of water. Furthermore, it does not follow that the greater the porosity, the greater is the volume of air contained. A heavy clay which is highly porous may, under field conditions, be so poorly aërated as to have developed within it semi-anaërobic conditions.

Ordinary moist soils, under field conditions, contain a quantity of air equivalent to 10 or more percent of their unit volume. In a soil with a well-prepared seed bed, the volume of air approximates 20 or 25 percent.

Composition of soil air. The nitrogen content of the atmosphere averages 75.5 percent by weight and 78.1 percent by volume, and the oxygen content averages 23 percent by weight and nearly 21 percent by volume. The normal atmospheric content of carbon dioxide is 0.03 percent, by volume.

Air in aërated soils has about the same nitrogen content as that of the atmosphere. But owing to biological activities (microorganisms and plants), chemical reactions, and diffusion of gases, the percentages of carbon dioxide and oxygen may vary greatly.

Boussingault and Lewy (Fr., 1853) found a carbon dioxide content of 9.74 percent (by volume) and an oxygen content of 10.35 percent in a sandy soil 10 days after it had received manure, including 3 days of rain. Schloesing, Jr. (Fr., 1889) found from

0.5 to 11.5 percent of carbon dioxide, and from 10 to 20 percent of oxygen in pasture land.

Russell and Appleyard (Eng., 1915) found from 0.01 to 1.4 percent of carbon dioxide and from 18.0 to 22.3 percent of oxygen in an unmanured soil, as compared with percentages ranging from 0.03 to 3.2 percent of carbon dioxide and from 15.7 to 21.2 percent

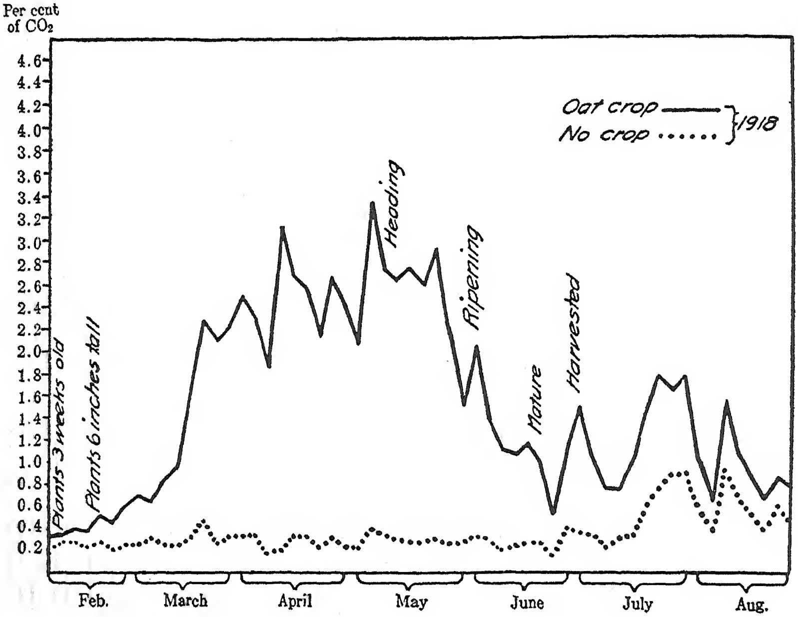

Fig. 70. Carbon dioxide in the air of clay-loam materials in cylinders, cropped with oats and left bare. Roots of growing plants affect materially the carbon dioxide content of soil air. (After Turpin.)

of oxygen in dunged soil. In grassed land they found from 0.3 to 3.3 percent of carbon dioxide, and from 16.7 to 20.5 percent of oxygen.

Leather (India, 1915) found as high as 12.03 percent of carbon dioxide and as low as 7.71 percent of oxygen in the surface 6-inch layer of a soil to which had been added green manure. In swamp rice land he found 4.42 percent of carbon dioxide and 0.54 percent of oxygen (Ch. 4).

Turpin (1920) observed that the air in soil materials growing oats and millet analyzed as high as 3.34 percent carbon dioxide for oats and practically the same for millet, as compared with

0.389 percent and 1.145 percent, respectively, in uncropped cylinders (Fig. 70).

Plants increase CO_2 in soils. It is generally agreed that soil bacteria is probably the most important factor in the production of carbon dioxide in tillable soils. Crop plants, however, increase the quantity of carbon dioxide either through excretions from their roots or through increased decay of organic matter effected by roots (Fig. 70). Some investigators believe that plants excrete from their roots certain substances which bacteria find suitable to their needs or which favor their development, because the bacterial population in immediate contact with roots is much more dense than it is a fraction of an inch away.

Leather found a much greater quantity of carbon dioxide and a much smaller quantity of oxygen near roots than in fallow soil. Neller (1922) observed much more rapid oxidation under cropped conditions than uncropped, other conditions being equal. Growing roots of buckwheat, barley, soybeans, and field peas had a direct effect upon decomposition of soil organic matter. Neller suggested a symbiotic relationship between growing plants (roots) and oxidizing organisms.

A second soil atmosphere. Russell and Appleyard (Eng.) have obtained evidence of a second or dissolved atmosphere in soils, which consists mainly of carbon dioxide with some nitrogen. They have found that after the ordinary soil air is removed, carbon dioxide slowly evolves, seemingly from the soil moisture, colloidal materials, and probably also from minute interstices within compound particles. This would indicate that even within properly tilled soils there may be points or places at which anaërobic condition exists.

Soil aëration. Romell (Swed., 1922) has estimated that for each square meter of soil surface, about 7 liters of carbon dioxide are evolved daily, which escapes from soils and is replaced by oxygen from the atmosphere. On this basis, and taking a depth of 20 centimeters (7⅞ inches), he has formulated a standard for *normal aëration* of soils. For a daily production of 7 liters of carbon dioxide per square meter of surface, it would require the complete renewal of the soil air every hour to a depth of about 8 inches in order to maintain its normal composition.

Cannon (1925) has shown that temperature is an important

factor affecting the relation between deficiency of oxygen and growth of plant roots.

Although tillage may increase the air content of soils, as in a well-prepared seed bed, adequate soil aëration cannot be effected by cultivation alone. Through land drainage, improved conditions allow and facilitate soil aëration.

Soil aëration is effected naturally in five principal ways: (1) by change in soil temperature; (2) by change in soil moisture; (3) by change in barometric pressure; (4) by the effect of wind; and (5) by interdiffusion of gases.

Change in soil temperature that takes place daily affects soil aëration principally in the surface layers, owing to the fact that the daily temperature wave penetrates soils to only shallow depths. Assuming, under most favorable theoretical conditions, that the warm air which passes out of the surface layers sets up a rather slow, upward stream of soil air, Keen (Eng., 1931) has estimated that aëration by daily change of soil temperature amounts to only about one eighth of the normal-aëration standard which has been formulated by Romell.

Change in soil moisture causes soil aëration in a simple way. Any quantity of water which a soil absorbs displaces an equivalent volume of air; and as the quantity of water decreases, the volume of soil air increases. Aëration in this manner is intermittent, and the total effect is small.

Change in barometric pressure occurs with regular periodicity. Change in pressure is transmitted to a considerable depth in soils and to the air in the minute interstices. Under this force, aëration is effected by contraction and expansion of the soil air, causing, respectively, a volume of atmospheric air to enter a soil and a part of the soil air to leave the soil. According to Buckingham (1904), ordinary barometric change of 2 centimeters in 12 hours affects aëration in a very deep soil to a depth of less than 8 centimeters, under theoretically ideal soil conditions. Thus under field conditions change in barometric pressure affects soil aëration to a very limited degree, as compared with the normal-aëration standard. The air pressure in soils may deviate from atmospheric pressure, owing to changes in atmospheric pressure and temperature, and to rainfall.

The effect of wind on soil aëration is localized, and is transmitted to only shallow depths. In moving over the ground, winds

cause increased pressure on the windward side of surface obstructions, and cause reduced pressure on the leeward side. These differences in pressure result in air movements in soils. Wind passing over a rough surface probably exerts a drawing effect on soil air. Romell has estimated the effect of ordinary wind on soil aëration to be only a small fraction of normal-aëration requirements.

Interdiffusion of gases seems to be the principal factor concerned in soil aëration, the total effect of all other factors being quite insufficient to cause adequate exchange. Temperature, moisture, barometric pressure, and wind operate intermittently, but gaseous interdiffusion operates continually. Romell and Keen have concluded that under ordinary field conditions, soils can be aërated adequately by interdiffusion of gases. In fact, in the surface 6-inch layer of arable soils diffusion of carbon dioxide into the atmosphere and of oxygen into the soil takes place very rapidly. Smith and Brown (1931, 1932) have concluded that soil respiration is not a simple diffusion of carbon dioxide through soils, and that diffusion of carbon dioxide cannot be regarded as an accurate means for measuring the rate of carbon dioxide production in soils.

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REVIEW QUESTIONS

1. Explain why soil aëration is a factor in soil fertility. Give evidence (see Index).
2. How can farmers and gardeners meet the soil-aëration problem?
3. What is meant by "rawness" of subsoils? By its importance as a problem in soil management?
4. Explain, through the use of a diagram, a soil as an "air system."
5. Is there any probable relation between soil aëration and photosynthesis of some agricultural plants? Explain.

CHAPTER 15

SOIL REACTION AND SOIL FERTILITY

The effects that soil materials produce on chemical indicators, such as litmus, are known as "soil reaction." These effects show that soils may vary widely, from very strongly acid to strongly alkaline reaction, indicating wide differences in their chemical nature, particularly regarding their content of "lime" or calcium (Ch. 4). Strong acidity (deficiency of calcium) and high alkalinity (much calcium or other basic elements), which may greatly influence plant growth, are important factors affecting the fertility of soils.

A relation between the calcium content of soils and soil productivity was recognized by Ruffin in 1844, when he observed how destitute many of the exhausted soils of Virginia and Maryland were of "calcareous earth." In a closer observation, Contejean (Fr., 1881) discovered a definite relation between certain plants and the chemical nature of the soils in which they grew, and proposed a plant classification based on lime relations, as *calciphile* (lime-loving), *calcifuge* (lime-avoiding), and *indifferent.* Hilgard (1906) also recognized a relation between "lime," or calcium, and plant growth.

In his sketch of the phytogeography of Belgium, Massart (1910) noted that for certain plants that grew only in calcareous mediums an abundance of lime proved to be beneficial, whereas for other plants that grew only on acid soils, lime was especially harmful.

An abundance of lime in soils may so affect the chemical nature of a plant as to influence, in turn, parasitic plants which may grow on it. Laurent (1890-1900) observed such a phenomenon in Belgium, where he found mistletoes (*Viscum album*) especially abundant in regions of calcareous soils, and none where the soils were poor in lime.

Alkalinity v. acidity. There are plants of various kinds that require considerable calcium, such as sweetclovers (*Melilotus*), cliff-roses, or quinine bushes (*Cowania*), guayule (rubber), and alfalfa

(*Medicago sativa*) (Fig. 71), whereas many other plants are known particularly for their low calcium requirement, including blueberries (*Vaccinium* spp.), huckleberries (*Gaylussacia*), cranberries (*Oxycoccus*), mountain-laurels (*Kalmia*), wintergreens, and heaths, which grow naturally only on acid soils.

The mediums of desert and semidesert plants are distinctly alkaline in nature. Among the plants that grow naturally under these

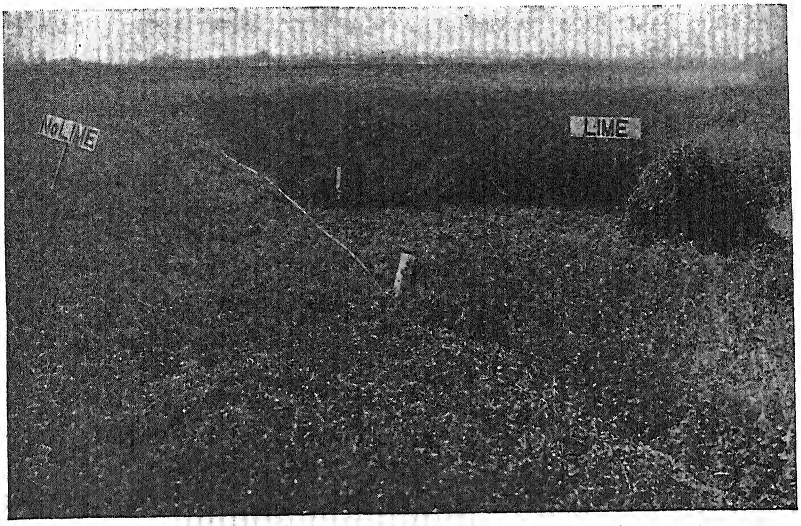

Fig. 71. Alfalfa plants grow best in nonacid soils, or those which are well supplied with calcium and magnesium. Left—Acid soil, unlimed, and plants adequately inoculated. Right—Acid soil, limed, and plants inoculated in same manner as on plot to the left. The soil in this field has developed from residual geologic material derived from limestone (now occurring at a depth of 3 feet). The soil material is strongly acid within 1 inch of the disintegrated limestone.

alkaline conditions may be mentioned cacti, sagebrush shrubs (*Artemisia* spp.), rabbitbrush shrubs (*Chrysothamnus*), mesquites, saltgrass (*Distichlis stricta,* Torr.), and greasewood shrubs (*Sarcobatus vermiculatus*). (Fig. 35.) Breazeale (1926) has pointed out that the tolerance of crop plants for alkali salts may be regarded as an adaptation phenomenon, in which available calcium, even in very small quantities, may be a potent factor in the development of plant resistance to the harmful alkali.

Illick (1930) observed that in places where chestnut trees once composed a large percentage of the forest stands in Pennsylvania,

the acidic litter from these trees favored the growth of lime-avoiding plants like mountain-laurels and upland blueberries; but since the disappearance of the chestnut trees, owing to chestnut blight, these calcifugous plants have decreased considerably in number.

Acid-tolerance of plants. Although certain plants may be regarded as truly calcifugous, many kinds of plants that grow in acid soils are not necessarily lime-avoiding. Such have been classed as *acid-tolerant*, whereas those that can grow in particularly acid mediums have been classed as *acidophile* (calcifugous). Coville (1913) applied the concept of acid-tolerance to crop plants, and he grouped 16 species in this class, including maize, oats, potatoes, strawberries, blueberries, cranberries, blackberries, raspberries, sweetpotatoes, rye, millet, buckwheat, redtop, carrots, and turnips.

It was once thought that "soil acids" had an injurious effect on plant roots, but it has been shown that ordinary soil acidity does not injure the roots. Truog (1918) and Hoagland (1919) have established the fact that the reactions of root sap of most agricultural plants range in hydrogen-ion concentration from pH 4 to 6 (very acid to slightly acid), thus indicating that roots are able to stand high degrees of acidity.[1]

Soil reaction involves something more than simply the calcium relation between soils and plants. On the contrary, much greater significance is to be attached to soil reaction, particularly as a factor in soil fertility. It may involve toxicity of soluble substances like aluminum and manganese, nitrogen assimilation by plants, and chemical reactions in soils that affect the availability and intake (by roots) of mineral nutrients. Soil reaction may also affect the activity of soil micro-organisms, plant diseases, competition between plant species, and physical soil properties. Thus the relation between soil reaction and soil fertility is exceedingly complex.

Soil reaction and toxicity. In some soils a high degree of acidity may indicate a condition that would favor solubility of aluminum, and therefore the development of toxic concentrations of aluminum compounds in the soil solutions. Aluminum is practically insoluble at reactions that range from pH of about 5 to 8.5. Below and above this range, solubility of this element increases. It was Veitch who first recognized a relation between soluble alumi-

[1] Hydrogen-ion concentration of pH 7 represents neutral reaction; below pH 7 is acidity; above pH 7 is alkalinity. Alkalinity results from an excess of hydroxyl ions (OH) over hydrogen ions (H).

num and soil acidity, in 1904. In the study of reclamation of certain Indiana marsh soils, Abbott and co-workers (1913) found that the quantity of aluminum (present as nitrates) in an unproductive acid soil was directly proportional to the quantity of alkali required to neutralize the soil solution.

Daikuhara (Jap., 1914) and Conner (1916) have associated soil acidity with the presence of salts of iron and aluminum. Kratzman (Ger., 1914), Rice (Wales, 1916), Miyake (Jap., 1916), and Mirasol (1920) have linked the presence of soluble aluminum with harmful effects of soil acidity.

Ruprecht and Morse (1915-1917) found that when acid-forming ammonium sulphate was added to soil materials, it dissolved out calcium first and then it attacked the iron, aluminum, and manganese compounds, bringing the last three elements into solution, and showing how acidity might bring into action toxic substances like aluminum and manganese.

Hartwell and Pember (1918-1919) have suggested that a distinction should be made between a deficiency of calcium, for example, and toxicity, as of aluminum. They found barley to be more sensitive than rye to soil acidity, owing to its greater sensitiveness to active aluminum ions. Nehring (Ger., 1928-1934) found barley more sensitive than oats to aluminum. Active aluminum or its toxicity, consequent to soil acidity, has been accepted by several investigators. McGeorge and co-workers (1926) have found, in Arizona, that black-alkali soils contain appreciable quantities of water-soluble aluminates which act as mobile carriers of aluminum in such soils.

The fact of true aluminum toxicity has been established by McLean and Gilbert (1928) who have demonstrated that aluminum as citrate is toxic to plants in culture solutions with acidity of pH 6. Furthermore, Gilbert and Pember (1931) have shown that active (toxic) aluminum has a greater inhibitory effect on the growth of lettuce and barley in soil and water cultures than has acidity. From a study of acid-soil materials representing 30 widely different types of soils of 9 States, Pierre and co-workers (1932) have obtained data which show that toxic aluminum may be an important factor in the relation of soil acidity to soil fertility. They also found that soluble soil aluminum varies greatly. Turner (B. W. I., 1931) has found that aluminum is invariably

present in soils with pH less than 5.1, though the relationship is irregular.

The explanation of the toxicity of aluminum salts given by Hissink (Holl., 1925) is that these salts cause a high concentration of hydrogen ions in the cell sap, and that a high concentration of anions around the roots interferes with both transpiration and intake of nutrients.

Mention has already been made of the facts that in submerged soils accumulated carbon dioxide (temporary acidity) is mainly responsible for holding iron, manganese, and other basic elements in solution; and that under such saturated conditions, toxic concentrations of ferrous iron, sulphides, and manganese may develop (Ch. 14).

In some soils, acidity may cause development of toxic concentrations of manganese in the soil solutions, as Funchess (1918) has found in acid Alabama soils. Emmert (1931) obtained results that seemed to indicate that in an acid manganiferous bluegrass soil in Kentucky sufficient manganese may dissolve to injure the growth of lettuce and tomatoes, and to cause blanching of the chlorophyll. Jacobson and Swanback (1932) have reported evidence of soil acidity causing manganese toxicity to tobacco in Connecticut, as indicated by definite abnormalities in growth.

Soil reaction and nitrogen assimilation. An established fact is that the reaction of the mediums in which plants grow is an important factor in nitrogen assimilation. Prianishnikov (Russ., 1929) and other investigators have demonstrated that some plants, particularly during early growth, can assimilate nitrogen in the ammonium form (NH_4) so long as the reaction of the mediums remains about neutral or slightly acid; but that when the mediums are made distinctly acid, ammonium nitrogen is injurious, and nitrate nitrogen (NO_3) is then the best form for assimilation. This problem is further discussed under "nitrogen fertilizers" in Chapter 21.

Reaction of soils and mineral nutrition. The importance of calcium and magnesium in relation to plant nutrition is discussed in Chapter 17, which deals with the science and art of liming acid soils. Soil acidity may also seriously interfere with plant absorption and assimilation of essential iron, manganese, and phosphorus.

Soil alkalinity, as well as acidity, may limit the producing power of soils. Studying the ill effects of calcium on perennial lupines,

Pfeiffer and Blanck (Ger., 1914) obtained data that indicated that the injury from calcium was due partly to its effect on iron assimilation, which they found was retarded by both limestone and potassium nitrate. Hiltner (Ger., 1915), in a similar inquiry, found that lime-induced chlorosis of lupines and other plants could be obviated by spraying the plants with solutions of iron salts. In regard to the injury to lupines by lime, he concluded that it was due to the action of the lime on the nodule bacteria. Sidorin (Russ., 1914-1916) held the view that chlorosis of plants in alkaline mediums might be caused by inaccessibility or lack of assimilation of iron. Too high a degree of alkalinity and high concentration of lime carbonate may also depress the solubility of soil potassium.

In his study of calcifuge manifestations of sphagnum (moss), Paul (Belg., 1918) observed that these plants secreted certain acids which proved to be indispensable to their nutrition, and that neutralization of these acids resulted in injury to the plants.

Gile and Carrero (1920) obtained strong evidence to indicate that lime in calcareous soils may cause a loss of green color in rice and pineapples, owing to precipitation of soluble iron, and consequent deprivation of the plants of this essential nutrient element. Coville (1926) definitely showed that such plants as rhododendrons, *Franklinia* trees, and blueberries can grow normally in good upland soils that have been acidified with aluminum sulphate.

The color of hydrangea flowers can be regulated by soil reaction, as established by Molisch (Holl., 1897). In neutral or slightly alkaline soils, the flowers may be pink; but when the soils are made acid by aluminum sulphate, the flowers become blue. Or when a hydrangea plant with pink flowers is transplanted from a pot of neutral soil to a strongly acid soil, the subsequent flowers may be blue. The explanation of these color changes is to be looked for, respectively, in the insolubility and solubility of aluminum, as shown by Allen (1931) and Chenery (Eng., 1937).

Pineapples on manganiferous soils of Hawaii would develop chlorosis if they were not supplied with soluble iron through spraying with iron sulphate, as developed by Johnson (1917, 1924).

The availability of manganese in soils may also be greatly affected by soil reaction. Observing that chlorosis in plants, caused by a deficiency of manganese, was closely associated with heavy applications of nonmagnesium lime, Willis (1929) has suggested that Coastal Plain soils be not limed any more than to effect re-

actions above pH 6.5 (slightly acid), except for such crops as are easily injured by acid-soil conditions. In many instances Coastal Plain soils of North Carolina have been found so deficient in magnesium as to call for the addition of some magnesium compound, in order to meet crop requirements.

Soil phosphorus may be rendered insoluble as the consequence of strong acidity. Many investigators have found that acid soils are more commonly deficient in available phosphorus than soils that are neutral in reaction or only slightly acid, owing to the fact that in the former soils the phosphorus occurs largely as iron and aluminum phosphate of low availability. Ford (1932-1933), investigating some Kentucky soils, found that soil phosphorus decreased in availability with increase in acidity, particularly in certain acid soils that are rich in iron, because of the fixation of phosphorus by hydrated ferric oxide of iron (gothite, limonite, $2Fe_2O_3 \cdot 3H_2O$).

Alkaline mediums represent quite different conditions regarding soil phosphates, as Prianishnikov (Russ., 1911), Hoagland (1917), and McGeorge and Breazeale (1932) have shown. The last two investigators have found that calcium phosphates are very easily soluble in mediums having acid reactions and very insoluble at alkaline reactions, whereas with iron and aluminum phosphates and phytin (organic), solubility is greatest in mediums having alkaline reactions—results which agree with those obtained by the other investigators. Alkalinity also affects absorption of nutrients by plants. With wheat seedlings, Breazeale and LeClerc (1912) demonstrated that alkalinity has a depressing effect on the absorption of phosphorus and nitric nitrogen. In Arizona, Breazeale and McGeorge (1932) have obtained evidence that would indicate that infertility of black-alkali soils is caused principally by the inability of plants to absorb phosphorus and nitrate nitrogen in the presence of hydroxyl ions (OH), owing to the absence of carbon dioxide (see Index). They found that wheat seedlings absorbed and assimilated phosphorus least readily at reactions ranging from pH 8 to 9, and that there was no absorption of phosphorus until the reaction of the root-soil contact zone was reduced to pH 7.6 by carbon dioxide exudation. These investigators have found that when a plant is grown in an acid soil (pH 5), the roots will increase the pH value in the soil around them to about 6.8; and

when grown in an alkaline soil (pH 8.5), will decrease the pH value to about 6.8. High pH may decrease available calcium.

Soil reaction and micro-organisms. Soil reaction may profoundly affect soil micro-organisms. The development and activity of bacteria, including those that effect decomposition (decay) of organic matter and certain chemical compounds, nitrification, and nitrogen fixation, are inhibited or stopped by strong acid conditions, whereas most fungi seem to favor an acid environment.

Ramann and co-workers (Ger., 1899) found that bacteria predominated in neutral and alkaline soils, while fungi were more abundant in acid soils. Jensen (Den., 1931) has shown that this is true only to a limited degree, as the addition of lime to acid soils does not markedly depress the number of fungi. He found that food supply is an important factor in the growth of fungi, and that with the exception of actinomycetes, fungi can usually stand higher acidity than can bacteria. In soils that have acidity of pH 4, none or only a few bacteria may be present, but fungi may be present in abundance.

Attention is called to nonpathogenic fungi that form mycorhiza, or symbiotic growth, on roots of higher plants, particularly in acid soils that are rich in organic matter. Falck (Ger., 1923) and Melin (Swed., 1924) have found most abundant mycorhizal fungi in acid woodland soils, such growths being necessary in acid soils to supply plants with nutrients, especially nitrogen. According to Rayner (Eng., 1928), orchids, rhododendrons, azaleas, mountain-laurels, blueberries, huckleberries, wintergreens, and heaths have mycorhizal fungi on their roots. It is known that mycorhizal growths also occur on the roots of most trees that grow on acid soils, including chestnuts, beeches, oaks, and conifers, and on mosses, ferns, and other acid-soil plants.

Knowledge of mycorhiza dates from 1885, when Frank (Ger.) applied the name to tree roots that showed a regular characteristic infection by mycelium of fungi. As expressed by Rayner, mycorhiza draws attention to the fact that in the plant world the severity of the struggle for existence commonly centers on the competition for suitable compounds of nitrogen. Without adequate nitrogen, plants weaken and are unable to meet competition; but with nitrogen, they develop strength and resistance. Many of the most striking adaptations known are directly related to the nitrogen problem, including the insectivorous habits of acid-loving plants

like sundews, Venus's-flytraps, and pitcherplants and the formation of nodules on leguminous plants by nitrogen-fixing bacteria (Ch. 5).

Soil reaction and pathogenic fungi. Many fungi that cause diseases of plants inhabit soils naturally or temporarily. Some of these pathogenic organisms, such as those which cause clubroot of cabbages, die when soil acidity is neutralized, whereas others cannot live in soils that have developed strong acidity.

In their investigation of some potato soils of northern Maine, Gillespie and Hurst (1918) found that typical Caribou loams, which varied in acidity from pH 4.8 to 5, produced potatoes free from scab, whereas typical Washburn loams, which had hydrogen-ion concentrations of from 5 to 6.6, usually produced scabby potatoes (see Index).

Soil reaction and plant competition. The relation of soil acidity and alkalinity to distribution of plants, already discussed, suggests soil reaction as a potent factor in plant competition. A few practical illustrations will be given.

In acid-soil areas it is common to observe sweetclovers, or melilots, take up their habitat and become the dominant plants along sides of country roads that had been surfaced with crushed limestone, because of the neutralization of soil acidity by lime-carbonate dust.

The effect of soil reaction in plant competition may be strikingly demonstrated by seeding a grass-and-clover mixture of Colonial bentgrass, red fescue, sweet vernal, Kentucky bluegrass, white clover, red clover, and black medic on two adjoining plots, one naturally strongly acid and the other made neutral by liming. On the first plot, plants that can grow under strongly acid conditions, like the bentgrass and fescue and sweet vernal grasses, will ultimately become dominant; while on the limed plot, plants like bluegrass, clover, and black medic will predominate.

Sheep sorrel weeds (*Rumex acetosella*) have been commonly regarded as indicators of acid soils, because they commonly become the dominant plants in hay fields. The explanation lies not in sheep sorrel weeds being "acidophile" but rather in the fact that they are able to compete successfully with plants that do not thrive on acid soils. Sheep sorrel may be benefited by liming.

Soil reaction and physical properties. The poor physical condition of many heavy clay loams and silt loams is closely related

to high degrees of acidity which may have been caused naturally through leaching or artificially through continual use of acid-forming fertilizers. On the other hand, good physical condition of heavy-textured soils may indicate alkalinity or slight acidity. The explanations lie in the phenomena of deflocculation and flocculation of colloidal soil materials (Ch. 4).

Soil-reaction favorable for plant growth. The following table represents an attempt to indicate the soil reactions that are favorable and unfavorable for various economic plants, based on investigation of their natural abodes, experiments and research, and of tests of soils and soil materials for which different plants have shown their adaptability by normal or optimum growth. The data have been compiled from many sources, including publications of agricultural institutions of both America and Europe, works of other investigators, and observations of the author.

In interpreting these data, cognizance must be taken of the fact that the supply of available nutrients is an important factor affecting the relation between soil reaction and the growth of certain plants. This may be typically illustrated by alfalfa, which may grow successfully on naturally rich soils of medium acidity and on medium-acid soils that have been heavily manured.

In the following table, favorable soil reaction is indicated by "X." It will be noted that some plants grow well or normally in soils that vary in reaction from strongly acid to distinctly alkaline. And, further, not only plants of different species, but also different varieties of the same species and different races of the same plant show optimum growth in soils that differ greatly in reaction.

Although some plants grow best in soils with a certain degree of acidity or alkalinity, they may grow fairly well or normally in soils that vary widely in reaction. Such cases are indicated by "x." With the exception of extreme acidity and alkalinity, a few plants seem to grow equally as well in acid as in alkaline soils, as is typically illustrated by carnations.

Reactions at which certain plants have not been found to grow or at which no attempt should be made to grow them are indicated by "o."

The scientific plant names given in the table, as well as throughout the text, conform to the International Code of Botanical Nomenclature adopted in 1930 at Cambridge, England, a code which has become the standard in the United States.

Soil Reaction in Relation to Growth of Economic Plants

Plants	Soil Reaction — X, most favorable reaction. o, unfavorable reaction. x, reaction at which plants may grow fairly well or normally.					
	Strongly Acid pH 4.8–5.4	Medium Acid pH 5.5–6.1	Slightly Acid pH 6.2–6.9	Neutral Reaction pH 7.0	Slightly Alkaline pH 7.1–7.8	Medium Alkaline pH 7.9–8.5
CROP PLANTS						
Alfalfa, lucerne (*Medicago sativa*)	o	x	x	X	X	x
Asparagus (*Asparagus officinalis*)	o	x	x	X	X	x
Barley (*Hordeum sativum*)	o	x	X	X	x	x
Beans, common white, navy (*Phaseolus vulgaris*)	x	X	X	x	x	—
Beans, lima (*P. lunatus macrocarpus*)	—	x	X	x	x	—
Beans, snap (*Phaseolus*)	x	X	X	x	o	o
Beans, velvet (*Stizolobium deeringianum*)	x	x	X	x	—	—
Beets, garden (*Beta vulgaris*)	o	x	X	x	x	—
Blackberries (*Rubus nigrobaccus*)	x	X	X	x	—	—
Blueberries (*Vaccinium*)	X	x	x	o	o	o
Buckwheat (*Fagopyrum esculentum*)	x	X	X	X	x	—
Cabbages (*Brassica oleracea capitata*)	x	x	X	X	x	x
Cacti (*Cactus*)	o	o	o	x	x	X
Cantaloups (*Cucumis melo*)	o	x	X	x	x	x
Carrots (*Daucus carota*)	x	X	X	x	—	—
Cauliflower (*Brassica oleracea, botrytis*)	x	X	X	x	x	x
Celery (*Apium graveolens*)	o	x	x	X	x	x
Corn, maize (*Zea mays*)	x	x	X	X	x	x
Cowpeas (*Vigna sinensis*)	x	x	X	x	x	—
Cranberries (*Oxycoccus*)	X	x	o	o	o	o
Cucumbers (*Cucumis sativus*)	x	X	X	x	x	o
Flax (*Linum usitatissimum*)	—	x	X	x	x	—
Grapes (*Vitis*)	x	x	x	x	x	x
Hemp (*Cannabis sativa*)	x	x	X	X	x	x
Horseradish (*Armoracia rusticana*)	x	X	x	o	o	o
Kale (*Brassica oleracea*)	x	x	X	X	x	—
Kohlrabi (*B. oleracea, caulo-rapa*)	x	x	X	x	x	—
Lettuce (*Lactuca sativa*)	o	x	X	x	o	o
Lupines (*Lupinus*)	x	X	X	x	o	o
Mangels (*Beta*)	o	x	X	X	x	—
Muskmelons (*Cucumis melo*)	o	x	X	x	x	x
Mustard (*Brassica*)	x	x	x	x	x	x
Oats (*Avena sativa*)	x	X	X	x	x	x
Onions (*Allium cepa*)	o	x	X	x	x	x
Peanuts (*Arachis hypogæa*)	x	x	X	X	x	—

Peppers (*Capsicum*)	x	x	X	X	x	x
Peas, Austrian field (*Pisum*)	x	x	X	x	x	—
Peas, canning or field (*Pisum sativum*)	x	X	x	x		—
Peas, garden (*P. sativum*)	x	x	X	x	x	—
Pineapples (*Ananas sativus*)	x	X	x	o	o	o
Potatoes, Irish or white (*Solanum tuberosum*)	x	X	X	x	x	o
Radishes (*Raphanus sativus*)	—	x	x	X	X	X
Rape (*Brassica napus*)	x	x	X	x	x	—
Raspberries (*Rubus*)	x	X	X	x	x	—
Rice (*Oryza sativa*)	x	X	x	o	o	o
Rhubarb (*Rheum rhaponticum*)	x	x	X	x	x	—
Rutabagas, Swedes (*Brassica campestris*)	x	X	X	x	x	—
Rye (*Secale cereale*)	x	X	X	x	x	o
Serradella (*Ornithopus sativus*)	x	x	X	x	x	o
Sorgo (*Sorghum vulgare* var. *saccharatum*)	x	X	X	X	X	x
Soybeans (*Glycine hispida*)	x	X	X	X	x	x
Spearmint (*Mentha spicata*)	x	X	X	o	o	o
Spinach (*Spinacia oleracea*)	o	x	X	X	x	x
Strawberries (*Fragaria*)	x	X	x	x	—	o
Sugar beets (from *Beta vulgaris*)	o	x	x	X	x	o
Sugarcane (*Saccharum officinarum*)	o	x	X	X	X	x
Sunflowers (*Helianthus annuus*)	x	x	X	X	x	o
Sweet corn (*Zea mays*)	x	X	X	x	x	—
Sweetpotatoes (*Ipomœa batatas*)	x	X	X	x	o	o
Tobacco (*Nicotiana tobacum*)	x	X	x	o	o	o
Tomatoes (*Lycopersicon esculentum*)	x	x	X	X	x	x
Turnips, common (*Brassica rapa*)	x	x	X	x	x	o
Turnips, Swedish, rutabagas (*B. campestris*)	x	X	x	o	o	o
Vetch, kidney (*Anthyllis vulneraria*)	o	x	X	X	x	o
Watermelons (*Citrullus vulgaris*)	x	x	X	x	—	—
Wheat (*Triticum sativum vulgare*)	x	x	X	X	X	x
CLOVERS AND GRASSES						
Bentgrass, creeping (*Agrostis palustris*)	x	x	X	x	x	x
Bentgrass, Colonial (*A. tenuis*)	x	x	X	x	x	—
Bentgrass, seaside (*A. maritima*)	o	x	X	x	x	x
Bentgrass, velvet (*A. canina*)	x	X	X	x	x	—
Bentgrass, white (*Nardus stricta*)	X	x	o	o	o	o
Bermuda grass (*Cynodon dactylon*)	x	x	X	x	x	—
Bluegrass, rough (*Poa trivialis*)	x	x	X	x	X	x
Bluegrass, Canada (*Poa compressa*)	x	X	X	x	x	—
Bluegrass, Kentucky (*P. pratensis*)	o	x	X	x	x	x
Bur-clover (*Medicago arabica*)	x	x	X	x	—	—
Clover, alsike (*Trifolium hybridum*)	x	x	X	X	X	x
Clover, crimson (*T. incarnatum*)	x	x	X	X	x	—
Clover, Hubam	o	x	x	X	X	x
Clover, Japan (*Lespedeza striata*)	x	X	X	x	x	—
Clover, mammoth (*Trifolium medium*)	o	x	X	X	X	—

Soil Reaction in Relation to Growth of Economic Plants—*Continued*

Soil Reaction: X, most favorable reaction. o, unfavorable reaction. x, reaction at which plants may grow fairly well or normally.

Plants	Strongly Acid pH 4.8–5.4	Medium Acid pH 5.5–6.1	Slightly Acid pH 6.2–69	Neutral Reaction pH 7.0	Slightly Alkaline pH 7.1–7.8	Medium Alkaline pH 7.9–8.5
TREES AND OTHER PLANTS						
Arborvitæ (*Thuja occidentalis*)	o	o	o	x	X	X
Beeches (*Fagus*)	X	X	x	o	o	o
Black ashes (*Fraxinus nigra*)	x	x	x	x	x	x
Cedars, white (*Chamæcyparis thuyiodes*)	X	X	x	x	o	o
Chestnuts (*Castanea*)	x	X	x	o	o	o
Elms (*Ulmus*)	x	x	x	x	x	x
Firs (*Abies*)	x	X	x	o	o	o
Fruit trees	x	X	X	X	x	o
Hawthorns (*Cratægus coccinea*)	—	x	x	X	X	x
Junipers, mountain (*Communis mont.*)	x	X	x	—	o	o
Junipers (*J. virginiana*)	o	o	o	x	X	X
Larches (*Larix laricina*)	o	o	x	x	X	X
Maples, sugar (*Acer saccharum*)	x	x	X	X	—	—
Mulberry (*Morus*)	—	—	x	x	X	x
Oaks, black jack (*Quercus marilandica*)	x	X	x	—	o	o
Oaks, red (*Q. rubra*)	X	X	x	x	o	o
Oaks, scrub (*Q. ilicifolia*)	X	X	x	x	o	o
Pines (*Pinus*)	X	X	x	—	o	o
Service berry, shadbush (*Amelanchier*)	x	X	x	o	o	o
Spruces (*Picea*)	X	x	o	o	o	o
Tamaracks (*Larix laricina*)	x	x	x	x	X	X
Thornapples (*Datura*)	x	X	x	x	o	o
Black medic (*Medicago lupulina*)	o	x	X	X	x	x
Crabgrass (*Digitaria sanguinalis*)	x	x	X	x	x	—
Dandelions (*Taraxacum*)	x	X	X	X	x	o
Daisies, wild (*Chrysanthemum leucanthemum*)	x	x	x	X	X	x
Groundpines (*Lycopodium obscurum*)	x	X	x	—	o	o
Heather (*Calluna vulgaris*)	X	X	x	o	o	o
Pondweeds (*Potamogeton*)	o	o	o	o	—	X
Poverty grass (*Danthonia spicata*)	x	X	x	x	—	—
Sheep sorrel (*Rumex acetosella*)	x	x	X	X	x	—
Sphagnum moss (*Sphagnum*)	X	x	o	o	o	o
Stoneworts, chara (*Chara*)	o	o	o	o	o	X
Sundews (*Drosera*)	X	x	o	o	o	o
Wintergreens (*Gaultheria procumbens*)	x	X	x	o	o	o

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REVIEW QUESTIONS

1. Discuss the relationship between soil reaction and plants, as affecting soil fertility. Give examples.
2. What is the true meaning of "acid-tolerant," as applied to plants?
3. Discuss the problem of toxic aluminum in soils. Give evidence.
4. How does the reaction of the medium in which a plant is growing affect its assimilation of nitrogen? Its assimilation of mineral nutrients? Give examples.
5. Explain how a plant may "resist" soil acidity and alkalinity. What significance has this fact regarding plant "tolerance"?
6. Explain competition between certain plants on the basis of soil reaction.
7. From all known facts regarding favorable and unfavorable soil reactions for plants, what fundamental principle is involved? Explain and illustrate.
8. What is meant by so-called "acid agriculture"?

CHAPTER 16

SOIL ACIDITY AND SOIL ALKALINITY

In the preceding chapter attention has been called to the fact that soil acidity indicates a deficiency of basic elements in a soil, principally calcium and magnesium. As it is commonly expressed, an acid soil lacks "lime." And soil alkalinity, on the other hand, may indicate a predominance of these two elements, or a prevalence of basic over acidic ions in the base-exchange compounds of a soil.

The discovery of acid soils was made through the use of litmus, a dyestuff which turns red in contact with acids and blue in contact with alkalies.[1] The fact that some soil materials react acid to litmus and that lime (CaO) and lime carbonate ($CaCO_3$) would neutralize this acidity have been known for some time. This knowledge gave rise to the idea of liming soils to neutralize the "acid" that was regarded as the harmful agent in acid soils or those with a deficiency of "lime."

Humic acid theory. At first it was commonly supposed, by Sprengel (Ger., 1826) and others, that organic acids, which originated through decomposition of soil organic matter and which accumulated particularly in wet and poorly aërated soils, were the cause of soil acidity. The fact that extracts obtained from soils by use of alkaline solutions contained acid organic compounds, called "humic acids," supplied a basis for attributing acidity of soils that contained considerable organic matter to these organic acids.

But when many well-drained, upland soils with little organic matter were found to be acid, soil chemists assumed that in such soils acidity resulted from the presence of certain acid mineral substances, the assumption being supported by the fact that silicates like kaolin were found to become more and more acid to litmus when treated with carbon dioxide solutions, as was shown by Gans (Ger., 1913).

[1] A source of litmus (a maritime lichen, *Rocella tinctoria*) was discovered by a Florentine in the thirteenth century A.D.

Selective-absorption theory. No one succeeded in isolating from any acid mineral soil a true acid in any significant quantity.[2] This failure gave rise to the so-called "selective-absorption" theory to explain soil acidity. Such a theory was advanced by Cameron (1905-1910), and subsequently by other investigators. This theory was based on the absorption action of soil colloidal materials, which was discovered by Van Bemmelen in 1878 (Ch. 4).

Cameron set forth the hypothesis that ordinary so-called "acid soils" could be explained by absorption, for he assumed that the weak base in blue litmus was absorbed by the colloidal soil materials which acted like absorbent cotton. Thus according to his explanation, soils that showed acid by litmus would not necessarily be acid at all. He regarded truly acid soils as being exceptional and abnormal.

Some investigators (Baumann and Gully, Ger., 1911) found that in case of acid peat soils, selective absorption seemed to explain all the known facts. But Tacke and Suchting (Ger., 1911), on thorough investigation, vigorously attacked this hypothesis, contending that acidity of humic acids could be explained only on the basis of true acids. Other investigators, including Harris (1914) and E. G. Parker (1914), concluded from their studies that acid reaction of upland mineral soils was caused by "selective" absorption of cations rather than by acids.

In his study of acid mineral soils of Japan and Korea, Daikuhara (1914) modified the explanation of acidity by introducing the idea of absorption. He found that when a salt solution was added to an acid soil material, an exchange of basic elements took place which brought aluminum and iron into solution. The solution would then react acid to litmus (by absorption), thus indicating soil acidity. This modified view was supported by Rice (Wales, 1916), who found aluminum nitrate in the solution that he obtained after treating an acid soil material with potassium nitrate solution, and by Kappen (Ger., 1916).

Acid clays. Loew (1913) concluded that the acidity of some soils of Puerto Rico was caused by acid clay which he called "argillic acid." This view was in harmony with what Ganssen (Ger., 1913) pointed out: namely, that it is possible for acid alumino-sili-

[2] A true *acid* may be defined as a substance that contains hydrogen that may be replaced by metals with the formation of salts. A *base* may be defined as a compound (usually a hydroxide of a metal) which upon reaction with an acid forms a salt and water. A *salt* may be defined as a compound formed when a base acts upon an acid.

cates to originate in the process of weathering; this conclusion is now an established fact.

Organic acids. The work of several investigators have established the fact that soluble organic acids occur in soils, particularly in peat. Schreiner and Shorey (1910) have found several complex organic acids in solutions obtained from soil materials by extraction with alkaline solutions. Moreover, it is known that amino acids and pentose compounds form in soils as the results of decomposition of proteins and celluloses.

Insoluble mineral acids. The failure of investigators to demonstrate that acid soils absorb equivalent quantities of basic elements in their neutralization constituted a strong argument against the occurrence of true mineral acids in soils. Although the work of Thompson (Eng., 1850), Way (Eng., 1850-1852), and Lemberg (Ger., 1876-1877) established the foundation for the base-exchange theory of soil acidity, up to 1916 no one seemed to have considered seriously the probability of the existence in acid soils of true insoluble mineral acids which in themselves could constitute a part of the physical make-up of soils.

In 1916, Truog reported results showing that in acid mineral soils equivalent quantities of different bases were required to neutralize the acidity, thus indicating that the cause of the acidity was acids that exhibited the properties of true acids. He pointed out that the acidity of most upland soils was caused principally by insoluble mineral acids like acid silicates, and that the reaction of those mineral acids was the consequence of their chemical constitution and not of their colloidal nature.

It is now generally accepted that in mineral soils the acidity phenomenon centers principally in complex, insoluble, aluminosilicates which occur in soil colloidal materials and which are only weakly acidic in nature. Colloidal soil organic matter is also concerned. Soil acidity is essentially a base-exchange phenomenon, and it is governed by the law of mass action and chemical equilibrium (Ch. 4). These facts and principles regarding soil acidity have been definitely established by several investigators.

Scientific determination of acidity. The presence of true acids in soils affords a basis for scientific study of soil acidity. In general, two principal types of methods are used in studying acids, as follows: (1) indicator or titrimetric methods in which indicators and standard alkali solutions are used to determine acidity values

in terms of volume of an alkali solution required to neutralize an acid solution; and (2) electrometric methods to determine concentration of hydrogen ions, in which reaction values are expressed, for example, as pH 7 for neutrality, pH 6.9 for the very weak acidity of saliva, pH 7.35 for the feeble alkalinity of blood, pH 1 for the acidity of a decinormal (N/10) solution of hydrochloric acid, and pH 13 for the alkalinity of a decinormal solution of caustic soda (NaOH).

Titration methods are used to measure the total quantity of acids or the total quantity of hydrogen ions in solution plus those that would finally be liberated on neutralization. But titration methods indicate no distinction between strong and weak acids. Moreover, in dealing with mixtures of unknown acids, complications arise, for the reason that titration values vary with different acids. Acids that have in a molecule more than one hydrogen atom replaceable by basic atoms or radicals give different titration values, depending on the number of hydrogen atoms or ions that are affected. Thus different indicators, which are used to designate the neutralization point or end-reaction, give different results. To illustrate: Litmus is suitable for reactions that range from acidity of pH 6 to alkalinity of pH 8; methyl red, for acidity from pH 4 to 6; methyl orange, for acidity from pH 3 to about 4.5; phenolphthalein, for alkalinity from pH 8 to 10; and bromthymolblue, for reactions from acidity of about pH 4.9 to alkalinity of about pH 7.4.

Some of the methods that have been devised for practical or rough determinations of the quantity of lime to apply to the acre are based on the titration principle.

Electrometric methods are used to measure the concentration of hydrogen ions that are actually present in acid solutions. These measurements of acidity are based on the theory of chemical dissociation—that is, chemical reactions (in water) in which associated molecules break down into ions. To illustrate:

$$\underset{\text{Hydrochloric acid}}{HCl} \rightleftharpoons \underset{\text{Chlorine ion}}{Cl^-} + \underset{\text{Hydrogen ion}}{H^+}$$

$$\underset{\text{Acetic acid}}{CH_3 \cdot COOH} \rightleftharpoons \underset{\text{Acetate ion}}{CH_3COO^-} + \underset{\text{Hydrogen ion}}{H^+}$$

Acids increase the hydrogen-ion concentration of water; in an acid soil, therefore, the acids present contribute to the concentra-

tion of hydrogen ions in the soil solution. On titration, as fast as the hydrogen ions that are in solution are neutralized by alkali, more of acid dissociates or ionizes, in order to maintain chemical equilibrium, in accord with the chemical law of mass action. In this manner more H ions are supplied until all that are dissociated are neutralized. In contrast, electrometric methods are used to measure the H ions that, at the moment, are present in solution.

Range of soil reactions. Determination of soil reactions by measuring hydrogen-ion concentration has become a common laboratory practice. Since 1916, following the adoption of Sörensen's (Den., 1909) method for expressing reaction measurements as pH values, a great many pH determinations of different soil materials have been made in different countries. Sharp and Hoagland (1916) found that it was possible to determine pH values of hydrogen-ion concentration in soil suspensions by use of a hydrogen electrode, and Gillespie (1920) developed a more useful method. These values range from acidity of pH 3.2 for some peat soils to alkalinity of from pH 9.7 to 11 for alkali soils that contain "black alkali," or sodium carbonate. Reactions of highly fertile soils commonly range from about pH 6.5 to 7.5.

Reactions of sap of plant roots range from pH 5 to 5.3 in buckwheat to about pH 7.2 in wheat.

Soil acidity in relation to hydrogen. The term "total soil acidity" has been defined as *the total quantity of hydrogen ions that may be produced in soil material when equilibrium is continually shifted to the end point by the introduction of hydroxyl ions* (OH).

Determination of soil acidity thus depends on replaceable hydrogen ions in soil base-exchange compounds. Dean and Magistad (T. H., 1931) have defined displaceable soil hydrogen as that quantity of hydrogen which if displaced by calcium will give a reaction of pH 7 (neutral).

A pH value of 6 represents 10 times the hydrogen-ion concentration of pH 7; and pH 5 represents 100 times the hydrogen-ion concentration of pH 7; and pH 4, 1,000 times.

In studying soil acidity, it is important to take into account both the strength and quantity of the soil acids. Effective soil acidity is determined by avidity and quantity of exchangeable hydrogen. According to Truog (1916) and F. W. Parker (1928), avidity of soil exchangeable hydrogen may be measured in terms of the percentage of hydrogen that may be displaced by potassium

on the introduction of neutral potassium acetate (CH_3COOK). The greater the avidity of the exchangeable hydrogen, the greater the percentage of hydrogen displaced by potassium.

Soil reaction and base-exchange. The base-exchange compounds in soils, both organic and inorganic, are colloidal materials. Their relation to soil acidity and alkalinity may be briefly explained in terms of mineral complexes as follows:

In a very acid soil, deprived of basic elements, the base-exchange compounds may be represented by the following chemical formula which is shown as being saturated with hydrogen and having no exchangeable cations:

$$xH(Al_2O_3 \cdot 4SiO_2 \cdot xH_2O)$$

Acting as a true acid, such a compound may contribute a large number of hydrogen ions to the soil solution. A measurement of this hydrogen-ion concentration may give a pH value, say of 4 or less.

If a normal neutral solution of potassium nitrate is added to some acid soil material, having a prevalence of H ions, a reaction will take place in accordance with the chemical law of mass action and equilibrium. Some of the hydrogen of the base-exchange compound, or insoluble mineral acid, will be displaced by an equivalent quantity of potassium of the solution added, and will form nitric acid in the solution. The reaction may be illustrated as follows:

$$\underset{\text{Solid soil phase}}{(Al_2O_3 \cdot 4SiO_2 \cdot xH_2O)\begin{cases} Ca \\ Mg \\ K \\ Na \\ xH \end{cases}} + \underset{\text{Solution}}{KNO_3} \rightleftharpoons \underset{\text{Solid phase}}{(Al_2O_3 \cdot 4SiO_2 \cdot xH_2O)\begin{cases} Ca \\ Mg \\ 2K \\ Na \\ (x\text{-}1)H \end{cases}} + \underset{\text{Acid in solution}}{HNO_3}$$

The percolate obtained will give an acid reaction, indicating that the soil represented is acid.

In the presence of a large quantity of sodium ions or continued sodium exchange, the base-exchange compounds may become saturated with sodium. Such a sodium-saturated compound hydrolizes easily, and may give rise to free sodium carbonate, or ''black'' alkali (Na_2CO_3). According to Breazeale and McGeorge (1926), the alkalinity of a black-alkali soil is caused by sodium hydroxide rather than sodium carbonate.

Hydrogen-saturated clays are acid clays, and they tend to disperse or deflocculate easily, causing topsoils to become hard and

lumpy, and subsoils to become impervious. Natural acid clays have been found in which exchangeable hydrogen constituted over 60 percent of the total exchangeable cations, or positive ions.

Calcium-saturated clays, which are nonacid, are commonly called "lime clays." They are usually permeable and crumbly, and are comparatively easy to till. Such clay soils are usually productive. Sodium-saturated clays, although nonacid, disperse and become impermeable much more readily than the acid clays, and hence they are unproductive and undesirable (Ch. 4). In the presence of sufficient calcium ions, both acid and sodium clays will absorb calcium, and as a result they will acquire characteristics like those of calcium clays.

Acidity and exchangeable basic elements. The principal exchangeable basic elements of soils are calcium, magnesium, potassium, and sodium. According to Kelley (1930), from 50 to 80 percent of the calcium in base-exchange materials is exchangeable, from 10 to 30 percent of the magnesium, and from 2 to 8 percent of the potassium and sodium. By prolonged electrodialysis, Bradfield and Schollenberger (1931) have removed practically all the calcium from the colloidal fractions of a number of clays. A pH value of 7 (neutral soil) may indicate a slight prevalence of exchangeable basic elements over exchangeable hydrogen.

Mention should be made of trivalent aluminum (Al^{+++}) and trivalent, or ferric, iron (Fe^{+++}) in relation to base-exchange. Magistad (1928) showed that these particular cations are not exchangeable—that is, soil base-exchange compounds do not contain trivalent aluminum and iron in exchangeable state.

In soils under field conditions, hydrogen ions are potent agents in driving basic elements out of soil base-exchange compounds. Ammonium ions also readily displace basic ions (p. 60), as in soils on which sulphate of ammonia is continually used as a fertilizer. The gradual removal of displaced basic elements from soils results in the development of, or increased, soil acidity. In reversing the acidifying process, or in improving acid soils, calcium or calcium and magnesium may be used effectively, not only in reducing or correcting the acidity of soils but also in driving sodium out of sodium clays, as in alkali soils.

In a soil under natural conditions, reaction of the topsoil material commonly differs from that of the subsoil (Fig. 72). This means that quite different conditions exist within such a soil, from

the surface downward: first, in connection with hydrogen-ion concentration or pH values; second, in the degree of saturation with basic elements; and third, in connection with active or soluble aluminum. Data that have been obtained by Conrey (1928) in a study of a forest silt loam of Ohio may be taken as an illustration.[3] These results and relationships are shown graphically in Figure 73.

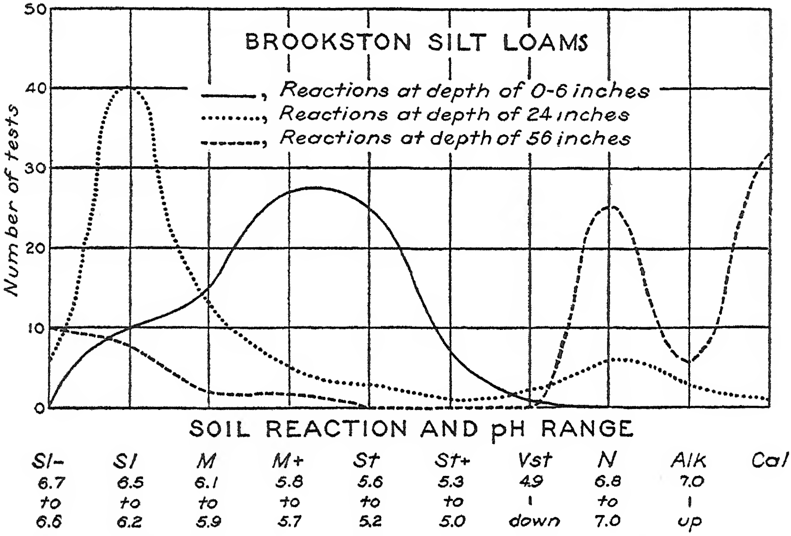

Fig. 72. Difference in reaction of topsoil, subsoil, and substratum of 69 soils classed as *Brookston silt loam,* central Indiana, under natural conditons. Reactions range from slightly acid (Sl) to calcareous (Cal). M, Medium acidity. St and Vst, Strong and very strong acidity. N, Neutral reaction. Alk, Alkaline.

Types of soil acidity. From the laboratory point of view, different types of soil acidity have been suggested by Kappen (Ger., 1916), including active or *free acidity, "exchange" acidity,* and *hydrolytic acidity.*

Active acidity is direct acidity that develops in a soil entirely depleted of exchangeable basic elements.

So-called "exchange acidity" is supposed to result from exchangeable aluminum which may be brought into solution by the displacing action of a neutral salt. Iron may also be brought into solution, which according to Trénel (Ger., 1929), may hydrolyze

[3] A soil classed as *Clermont silt loam* developed from very old calcareous glacial-drift material under poor drainage conditions, and under an average annual rainfall of 40.9 inches and average temperature of 55.2° F.

and produce an acid reaction. Goy and Roos (Ger., 1931) have pointed out that exchange acidity begins in soils with hydrogen concentration between pH 4.7 and 5.5.

Hydrolytic acidity has been so named because of its relation to the acidity that results from hydrolysis of a weak acid combined with a strong base, like sodium acetate, for example. In water,

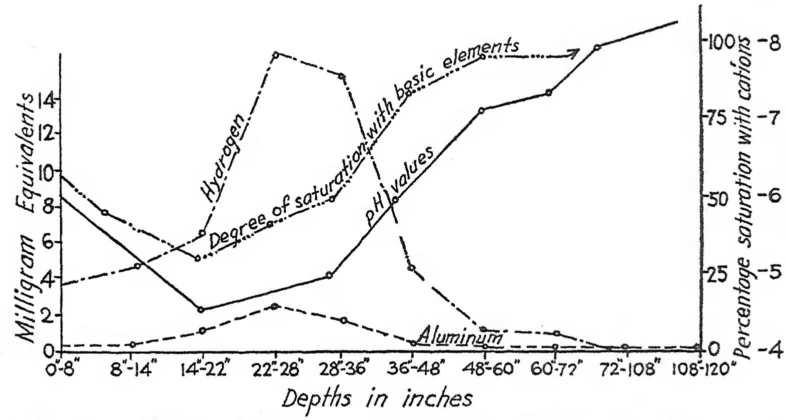

Fig. 73. Acidity or pH values, exchangeable hydrogen and aluminum, and the degree of saturation with basic elements in a soil classed as *Clermont silt loam* and its substratum, from the surface downward to a depth of 10 feet.

sodium acetate results in an alkaline solution, owing to hydrolysis of the salt. Here hydrolysis results in an excess of OH ions over H ions. The dissociation reaction may be expressed as follows:

CH_3COONa	$\rightleftharpoons$	CH_3COOH^-	$+$	$Na^+ \cdot OH^-$
Sodium acetate (Weak acid with strong base)		Acetic acid (Weak acid)		Sodium and hydroxyl ions

But when a sodium acetate solution is added to a slightly acid soil material, the absorptive substances absorb both the hydroxyl (OH) and sodium (Na) ions, leaving acetic acid in solution. Thus the percolate obtained will test acid, as in case of the addition of a neutral salt to an acid soil material. The acidity thus determined is called "hydrolytic acidity," and it is the weakest form that may occur in soils.

Acidity a complex phenomenon. The three types of acidity mentioned are based on fine technical distinctions, and they imply exchangeable aluminum and absorption of hydroxyl ions (OH).

Page (Eng., 1926) has stated that acidity of soils is essentially of *one* kind, owing to the fact that it is the consequence of exchangeable hydrogen ions. Nevertheless, the phenomenon of soil acidity is most complex, for the reason that an acid soil is a complex dynamic mixture of mineral particles, organic matter, soil solution, mineral acids, complex organic acids, ordinary chemical compounds, and micro-organisms.

Odén (Swed., 1927) has stated that the actions of acids and alkalies on soil materials are essentially chemical actions in heterogeneous mixtures, modified by colloidal materials. The fact remains, however, that the insoluble alumino-silicates and organic colloidal compounds (sometimes called "acidoids") constitute the principal seat of absorption and base-exchange phenomena.

Development of soil acidity. Acid reaction is a common characteristic of soils of humid regions. This relation between acid soils and precipitation implies natural development of acidity through the removal of basic elements from soils by percolating rain water, especially in humid regions.

One of the results of biological activities and ordinary chemical changes that take place in soils is the formation of acids. Acids, in turn, give rise to active hydrogen ions in the soil solutions, which slowly but gradually displace elements like calcium, magnesium, potassium, and sodium and drive them into solution as salts. As soluble salts, they may be readily removed from soils by percolation, ultimately resulting in a hydrogen-saturated condition.

Removal of basic elements is particularly effective in well-drained soils of level areas, so that in humid regions well-drained upland soils are more apt to be acid than mineral soils that occur in low meadows and those that may be annually flooded by waters that drain from limestone areas.

Factors in development of acidity. The principal factors in natural development of soil acidity are rainfall, temperature, kind of soil-forming material, organic matter, percolation, and kind and degree of weathering.

Rainfall and temperature effects may best be illustrated by two general facts which have been emphasized by Wiegner (Switz., 1918): namely, (1) Soil acidity decreases with rainfall, disappearing entirely in regions of limited and slight precipitation; and (2) soil acidity decreases, within certain limits, from humid cool to humid tropical regions, owing to increased decomposition and re-

moval of organic and inorganic base-exchange complexes (acidoids) and silica compounds, with the consequent relative accumulation of sesquioxides (aluminum and iron). (Ch. 6.) Soil acidity may increase, generally, with altitude—for example, in Arizona, from millions of acres of alkaline soils of low deserts to millions of acres of acid soils (including podzols) on the high Colorado Plateau.

Kind of soil-forming material is an important factor that affects not only the rate of acidity development, but also the degree or intensity of acidity. For examples: Under humid conditions, soils that develop mainly from silica sand may become distinctly acid even during incipient stages of development. On the other hand, in soils that develop from geologic materials that contain large quantities of slowly decomposable basic or calcareous mineral particles, development of any appreciable acidity in their topsoils may require many thousands of years.

Organic matter differs as greatly in effecting soil acidity as it differs in kind and source. The complete decomposition of surface forest litter (leaves, principally) is an important factor in the development of acidity that characterizes forest soils, the active acid-development agents being organic acids that result from litter decay. The chemical constitution of leaves is also an important factor, as is indicated by the well-known acid-producing properties of pine, oak, and chestnut leaves (see Index).

In contrast, one may mention the plant residues of true-prairie grasses. Here, owing to partial decay of underground roots, organic matter and humus have accumulated in soils to a considerable depth, aiding in effecting conservation of soil "lime."

Percolating rain water is the active agent in removing basic elements from drained soils, and the lack of percolation accounts for the fact that mineral soils developed under saturated conditions in humid regions are commonly not acid or only slightly so.

Character of soil material and kind and degree of weathering determine not only the nature of soil acidity in different types of soils, but also differences in reaction or acidity of topsoils and subsoils. In soils that, under natural conditions, have more acid subsoils than topsoils, the greater acidity of the B horizons may be attributed mainly to accumulations of colloidal mineral acids (acidoids).

From a study of 13 widely different types of soils of Alabama, Arkansas, Missouri, Illinois, and Wisconsin, Baver and Scarseth

(1930) have concluded that there are different types of soil acidity, as may be determined by kind and degree of weathering. The soil base-exchange compounds may develop in three ways: (1) by removal of certain constituents from the original alumino-silicate minerals; (2) by mutual flocculation of colloidal oxides of aluminum, iron, and silicon; and (3) by precipitation of aluminum, iron, and silicon from solution.

Origin of soil base-exchange compounds. The fact that inorganic soil base-exchange compounds universally occur in soils indicates that they are of secondary origin, arising from the weathering of soil-forming materials. Truog and Chucka (1930) have suggested that these inorganic compounds are formed from feldspars under alkaline conditions of weathering. In the processes of soil formation, soil materials are subjected to both acid and alkaline weathering. They have obtained data which indicate that between rains and periods of leaching the film water around soil particles of feldspars comes to a reaction of pH 8.4, a chemical condition that favors gradual development of base-exchange materials.

Soil acidity from other causes. Extremely high acidity has been found in soils that occur near ore-smelting plants, owing to formation of sulphuric acid from sulphur deposited as fumes and "flue dust." The sulphuric acid thus formed is a powerful agent in competing for soil basic elements; after that the acid may accumulate sufficiently to injure grass and other crops.

Soil acidity may also develop through continual use of acid-forming fertilizers like sulphate of ammonia, $(NH_4)_2SO_4$, ammonium chloride, NH_4Cl, urea, $CO(NH)_2$, ammonium phosphates, and Leunasalpeter (double salt of ammonium sulphate and ammonium nitrate). The acidifying action of such fertilizers is explained in Chapter 22.

Acidifying soils. It may be necessary to acidify soils, usually through the use of aluminum sulphate. To lower soil reaction from pH 7.7 to pH 6, requires 100 cubic centimeters of sulphuric acid or 13.3 ounces of aluminum sulphate per square yard. Acid peat moss may be used to develop soil acidity for such plants as young nursery conifers, and for rhododendrons, azaleas, and mountain-laurels. Elemental sulphur, sulphate of ammonia, and sulphur dioxide may also be used to develop and increase soil acidity.

For potatoes on scab-infested soils, powdered sulphur may be

used to increase acidity to a point (pH 5 to 5.4) that will not allow development of the disease organism (*Actinomyces scabies*). On soils that lack sulphur-oxidizing bacteria, it is advisable to use inoculated sulphur, according to Martin (1922), at rates varying from 300 pounds to 600 pounds an acre. Best results in scab control and disinfection may be obtained when the sulphur is broadcast just after the land is plowed and before disking in preparation of the seed bed.

Bermuda-grass lawns on calcareous soils are benefited by the use of acid-forming fertilizers, such as ammonium sulphate (see p. 287).

Cropping and removal of basic elements. The greatest loss of calcium, magnesium, and other basic elements from soils occurs during heavy precipitation and when the ground is bare of vegetation or crops. Under these conditions, the greatest percolation and leaching take place. Under cropped conditions, percolation and leaching are reduced, owing to utilization of water and nutrient elements by the crops.

At Ithaca, N. Y., percolation of about 21.5 inches of rain water through uncropped silty-clay-loam material has removed calcium, to a depth of 3.5 feet, at a rate equivalent to 900 pounds of pure limestone per acre.[4] Under cropped conditions, about 16 inches of rain water percolated through, removing calcium equivalent to 509 pounds of carbonate of lime per acre. The crops removed nearly 21 pounds of calcium per acre annually. Magnesium was removed in smaller quantities than calcium. Less potassium was removed by drainage water than by crops.

The quantity of basic elements removed by leaching varies according to soil, percolation, and soil treatment. At Blacksburg, Va., the annual loss of calcium through leaching has averaged only about 46 pounds an acre, being equivalent to 115 pounds of lime carbonate. From Broadbalk Field at Rothamsted, England, percolation of about 14.5 inches of rain water has caused an average annual loss of calcium equivalent to 710 pounds of carbonate per acre. The use of ammonium salts as fertilizer has increased this loss to 1,170 pounds. Here the soil has for years contained sufficient "lime" to maintain a neutral condition.

The quantities of calcium and potassium removed by crops are given in the table in Chapter 9.

[4] Material in lysimeters represented a soil, classed as *Dunkirk silty clay loam*, which has developed from glacial material originating from sandstone, shale, and limestone. Topsoil is acid, but at depth of 3 feet the material is nonacid.

SOIL CLASSES BASED ON ALKALINITY

Soils of four classes have distinct basic properties:

Alkaline soils. Soils that have pH values ranging from about 7.3 to 11 are *alkaline.*

Calcareous soils. Soils that contain free calcium carbonate (commonly with magnesium carbonate) in sufficient quantities to effervesce with hydrochloric acid are *calcareous,* also alkaline.

Alkaline-calcareous soils. *Alkaline-calcareous* soils characterize naturally drained areas of arid-semiarid lands. Their base-exchange compounds are saturated with calcium, sodium, and potassium in varying ratios, and they have pH values ranging from about 7.3 to 9.

Alkali soils. A soil that is poorly drained and contains either an excess of soluble salts or an abnormal quantity of absorbed sodium, or both, is an alkali soil, with pH value varying from about 8.5 to 11. According to McGeorge and Breazeale (1936), infertility of alkali soils may be explained by the fact that absorption of nitrate and phosphate ions by plants is inhibited in the presence of free hydroxyl ions (OH). (See p. 282.)

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REVIEW QUESTIONS

1. According to the base-exchange theory, distinguish between acid, neutral, alkaline, and alkali soils.
2. Explain the fundamental difference between titration and electrometric methods of determining soil acidity.
3. What three types of soil acidity have been suggested? Discuss.
4. What factors other than base-exchange are involved in soil acidity?
5. Discuss the factors that affect the development of soil acidity.
6. What constitutes the principal seat of soil-reaction phenomena? What is the remarkable fact about these materials? (Ch. 4.)
7. Describe soils that are represented by classes based on soil alkalinity.

CHAPTER 17

SCIENCE AND ART OF LIMING ACID SOILS

A deficiency of calcium and magnesium, or "lime," in acid soils may be corrected most economically through the use of any finely ground material that contains considerable quantities of calcium or both calcium and magnesium. The application of such materials to soils is called "liming."

Written accounts left by the Romans would indicate that "marling" the ground was practiced by the Gauls about 500 B.C. Burnt lime also was probably used in husbandry at a very early date, inasmuch as quicklime, produced from limestone, has been used for mortar since about the seventh century B.C.

Reference has been made to the fact that early development of civilizations took place in warm regions of limited rainfall (see Index). Movements of Roman civilization from warm regions into cool and humid countries did not begin until about 50 B.C., when Rome began to extend her empire westward. Thus it may be stated that agriculture developed on alkaline soils of warm countries, and in general, remained largely lime-soil husbandry until about the Christian Era.

Obviously, one of the new experiences of husbandmen under humid conditions was to find soils that were not alkaline. When lime (CaO) was first used on soils in humid regions is not known. Records of English writers who had visited Flanders as early as 1600 clearly show that the Flemish farmers, whose methods formed the basis of improved English husbandry (Ch. 1), knew nothing of liming, while the use of marl, chalk, and lime in husbandry was well known in England. In his account of Flemish husbandry in 1645, Weston (Eng.) wrote: "Wee [in England] have not only Dung to enrich our Land, but also Lime and Marl, of which they [in Flanders] know not the use." And in 1649, Blith (Eng.), in discussing the question of liming, wrote: "About 12 or 14 quarters of Lime will very well Lime an acre, you may also over Lime it, as well as under Lime it."

In 1625, Markham (Eng.) called attention to some old "marl" pits in Kent in which trees from 200 to 300 years old were growing, indicating that marling must have been an ancient practice. Although in these old pits Hall and Russell (Eng., 1911) have found no marl at all, but fuller's earth, it would seem from the facts cited that liming and marling must have developed in Gallia (France) and Britannia (England and Wales) at very early dates, probably with the introduction of Roman culture, and that it was revived during the Renaissance or during the early years of modern times (1500).

Early misuse of lime. The use of marl, chalk, and lime in agriculture long preceded knowledge of their chemical nature and of acid soils. Thus it is not surprising that we should find recorded evidence of the early misuse of lime and of difference of opinion regarding its benefits.

Prime importance of calcium. In soils, calcium is by far the most important basic element, for several reasons: (1) in its common forms or compounds, it is readily acted upon by water, and hence easily becomes an active basic element in soil solutions; (2) it combines directly with most elements, including nitrogen; (3) it is the principal cation in base-exchange compounds; (4) in relation to exchangeable elements in soils, calcium ions possess comparatively high displacement energy; (5) calcium forms compounds that are fairly stable in water; (6) it is an important factor in effecting availability and absorption of nutrient elements; (7) it is in itself a principal nutrient element; (8) absorbed calcium effects the greatest stability of the soil complexes; (9) it may increase the ion-exchange capacity of acid soils; (10) it imparts permeability to clays; and (11) it is an important element in the development of alkali resistance in crop plants. Magnesium may be regarded as ranking second in importance to calcium. Thus agricultural limes, which contain calcium and magnesium, are not only the most economical materials to use in soil improvement, but they have also proved to be the best, for the reasons indicated.

Detecting the need for lime. The need for "lime" on certain soils may be indicated in the following ways: (1) by failure of such crops as sweetclover, alfalfa, red clover, and other calciphilous plants; (2) by the dominant growth of such kinds of weeds as sheep sorrel, mayweed (*Anthemis cotula*), spurry (*Spergula arvensis*), and of certain mosses on lawns and grassed areas (see

Index); (3) on lawns and in pastures, by dominant growth of such grasses as bentgrasses, fescues, sweet vernal, and commonly by timothy and redtop (Ch. 16); by vigorous growth of crop plants on small areas where carbonate of lime, wood ashes, or lime plaster had been disposed of, or where the soil is not acid; (5) by the appearance of finger-and-toe or clubroot disease in fields cropped with rutabagas (Swedish turnips), turnips, and cabbages; and (6) by field experiments (Fig. 71).

Chemically, the need of most soils for lime may be determined by testing them for acidity. Whether small or large quantities of lime should be applied per acre may be indicated roughly by the degree of acidity. Several qualitative tests have been devised for testing soils, and also quantitative methods for determining how much lime is required to neutralize soil acidity.

Qualitative tests for acidity. Among the simple ways of testing soils for acidity and need for lime, the following may be mentioned:

The litmus-paper test, which was made by Voelcker (Eng.) as early as 1865, was commonly used in field work for 50 years. This test may be made by placing a piece of blue litmus paper in between two halves of a ball of fresh moist soil material (moistened with soft or distilled water), or by placing a strip of blue litmus paper on a piece of clean glass and pressing one half of a ball of fresh moist soil material firmly upon it. If, after about 2 minutes, the paper turns pink or red, the soil is acid.

The zinc sulphide test, devised by Truog in 1914, is based on the hydrogen-displacing action of calcium. Distilled water and a mixture of calcium chloride and zinc sulphide are added to a small quantity of soil material. On boiling, the calcium displaces hydrogen ions which unite with chlorine to form hydrochloric acid. The acid thus formed reacts with the zinc sulphide and generates hydrogen sulphide gas (H_2S). Hydrogen sulphide, in turn, reacts with moistened lead acetate paper which is placed over the mouth of the flask, darkening it according to the intensity of acidity and consequent liberation of hydrogen sulphide gas.

The potassium nitrate–litmus test, based on the well-known phenomenon of the absorption by soil material of the cation of a neutral salt solution, has also been used. This test may be made in the same way as the litmus-paper test, except that the soil ma-

terial is moistened with a saturated solution of potassium nitrate instead of lime-free water.

The Comber qualitative test, devised by Comber (Eng.) in 1920, consists in the use of a 4-percent alcoholic solution of potassium thiocyanate (potassium sulphocyanide, KCNS). In making this test, a small quantity of soil material is placed in a test tube or small glass vial, and a small quantity of the potassium thiocyanate solution is added. If, after standing, the solution remains clear, the test indicates that the soil represented is not acid. But if the solution turns red, the soil is acid, the degree of acidity being indicated by the degree of redness. Reactions in this test depend on displaceable iron in the soil material.

Other tests, based on the use of potassium thiocyanate, have been devised for use in determining the need of soils for agricultural lime.

The use of bromthymolblue for testing soils, suggested by Spurway in 1924, is based on the acid and alkaline reactions of the indicator named. This is one of the active agents used in Soiltex, in which reactions are indicated by the colors of the solution when it is brought in contact with very small quantities of soil material.

Other rapid soil-reaction tests have been developed, in which combinations of different indicators are used, such as LaMotte and Hellige and Truog Soil Testers.

Quantitative methods. A number of methods have been developed for determining not only the degree of soil acidity, but also the quantity of lime (CaO) required for its neutralization. Of these methods, the following four may be mentioned:

Veitch limewater method, devised by Veitch in 1902, consists essentially in titrating the acidity of a small quantity of soil material against a standard solution of limewater, $Ca(OH)_2$. Phenolphthalein is used as the indicator of neutrality or end reaction (Ch. 16). The quantity of limewater used measures the acidity, and from this may be calculated the quantity of lime (CaO) required per acre, within a few hundred pounds, to neutralize the acid in a soil to a given depth.

The Hopkins, Petit, and Knox method, perfected in 1908, is essentially a base-exchange method in which a normal solution of potassium nitrate is used. Acidity is measured by titration against sodium hydroxide (NaOH), and the quantity of lime required per

acre to neutralize acidity is calculated in a manner similar to that used in the Veitch method.

The Jones calcium acetate method (1907), as the name indicates, is based on the hydrolysis of calcium acetate, as in determining hydrolytic acidity (Ch. 16). Some investigators use this method to determine total soil acidity, including active, exchange, organic, and so-called "hydrolytic acidity."

The Hutchinson and McLennan method (Eng., 1914), developed to determine lime requirement of soils, consists essentially in treating a small quantity of soil material with N/50 solution of calcium bicarbonate, $CaH_2(CO_2)_2$, and titrating an aliquot part of the filtrate against a decinormal solution of acid, using methyl orange as indicator. There are different modified forms of this method.

Lime requirement. By lime requirement is meant the quantity of lime (CaO), or its equivalent in other forms, that is required per acre to neutralize the total acidity of a soil to a given depth. For the purpose of determining this requirement, many varieties of methods have been proposed, including the methods already mentioned. But owing to different soil conditions and to a lack of definite knowledge of the action of lime in soils, or of what happens to it after application, comparative results obtained by these methods vary greatly, and may be easily misinterpreted.

Results of lime-requirement methods have little or no economic value, and can have but little scientific significance in relation to soil fertility. From the laboratory point of view, however, they may have some theoretical value, in relation to the nonsaturation of soil materials or to the total quantity of absorbed hydrogen ions.

Truog (1918) has proposed inquiry into lime requirement from the point of view of the need of plants for lime, thus suggesting a plant-physiological method. Accordingly, he has proposed the expression "lime requirement of a plant" which refers to the ability of a plant to obtain the lime it requires. According to Truog, the following factors should be considered in such inquiry: lime content of plant, rate of plant growth, feeding power for lime, character and extent of root system, internal acidity of roots, and excretion of carbonic acid by plant roots.

Logically, the need of soils for lime concerns soil fertility. Both soil and plant factors, therefore, should be taken into account. In regard to the soils, physical, chemical, and microbiological factors are involved; and regarding the plants, the important factors in-

clude growth habits, nutrition, physiological conditions, soil reaction, and toxicity of substances like aluminum.

Neutralization of soil acidity. The quantity of lime required to neutralize the same degree of soil acidity in different soils may vary so widely as to make it impossible, with a single determination, to tell with any degree of accuracy the proper quantity of lime that would be necessary for their neutralization. For a sandy soil of pH 5, for example, much less lime is required than for a clayey soil with the same hydrogen-ion concentration. Moreover, the latter soil would require additional lime for the maintenance of permeability and good tilth. Some investigators have found that more lime is required to neutralize hydrolytic acidity than the same degree of exchange acidity.

The fact has been established that there is, in general, no close correlation between pH values of soils and their lime requirements. This may be explained as follows: Two acid solutions may show a very great difference in *intensity* of acidity, yet have the same *total* acidity, as may be demonstrated by two gram-equivalent solutions of hydrochloric acid (HCl, 36.5 g) and acetic acid (CH_3COOH, 60 g). The first solution, owing to a much higher degree of ionization, or concentration of hydrogen ions, will show greater intensity of acidity, or a lower pH value, than the second solution; yet both will require 40 grams of sodium hydroxide (NaOH) for their neutralization, indicating the same total acidity.

It has already been pointed out that intensity of acidity is determined by active hydrogen ions, or those that are actually present in solution; whereas total acidity is potential acidity, including the hydrogen ions in solution plus those that would finally be liberated on neutralization. Both acid solutions mentioned contain the same total number of hydrogen ions. Conditions similar to those just illustrated with respect to acidity probably exist in soils.

With many acid soils, particularly peats, the need for lime involves much more than simply neutralization of acidity. Chemical and biological factors are also involved.

Soil fertility does not depend on the presence of lime carbonate, nor does it follow that soils that are devoid of lime carbonate are infertile. The fact is that for most crop plants free carbonate of lime in soils is not required. For certain crops, some soils are fertile, despite the fact that they have low pH values, or high lime requirements.

Lime requirement of plants. Calcium and magnesium have been regarded as essential plant nutrients since 1804 (Ch. 16). For a century or more after that time, it was thought unnecessary to supply plants artificially with these two elements, as it was taken for granted that soils contained sufficient quantities to meet crop needs. Chemical analysis of soil materials seemed to prove this. The writings of Liebig (1858) on the role of plants in making mineral elements available, and the work of Sachs (Ger., 1860) and Czapek (Ger., 1896) on the dissolving action of plant roots on soil minerals also supported this view. However, when acid soils were discovered about 1865, liming was regarded as a means not for supplying available calcium and magnesium, but rather for neutralizing harmful acids.

In his study of 62 different crop plants, Truog (1918) found a very close relationship between their lime needs and their response, on acid soils, to liming, or reciprocally, to their growth in acid-soil mediums. This he found particularly true regarding sweetclover, alfalfa, red clover, sugar beets, garden peas, cabbages, and tobaccos.

Availability of calcium. Soil-plant relations should be considered in studies of calcium availability. Truog (1918) and Chapman (1929) found a close relation between the growth of alfalfa and quantity of available calcium. Parker and Pate (1926) and Tidmore and Williamson (1932) found that exchangeable calcium in strongly acid soils has low availability; whereas in nonacid (humid) soils, high availability. In alkali and alkaline-calcareous soils, plants may suffer for want of calcium, because exudation of carbonic acid from the roots is not of sufficient magnitude.

Benefits of liming. Many of the benefits that may result from liming acid soils have already been mentioned or suggested. However, a summary will be given in which the benefits are considered from the point of view of soil fertility, or soil-plant relations.

Lime flocculates clays. Heavy soils, or those that contain much clay, become more difficult to till when they become acid, owing to the fact that hydrogen-saturated or acid clays have a high degree of dispersion—that is, they "puddle" easily and become impermeable. Lime in sufficient quantities will reverse these conditions, and make such clays friable, permeable, and tillable. When calcium is applied to an acid clayey soil, it not only neutralizes

free or active acidity, but it also displaces the hydrogen cations of the acid clay material, changing it into calcium clay (Ch. 4).

Lime effects chemical changes. The first chemical change that takes place in soils on the addition of lime (CaO) and magnesia (MgO) is its reaction with carbonic acid, resulting in the formation of carbonates. In acid soils, immediate reactions may also include neutralization of active or toxic aluminum, neutralization of soil acids, and precipitation of excessive soluble iron.

Probably the most important chemical changes that are brought about by the addition of lime to acid soils involve base-exchange compounds of soils. Both calcium and magnesium become potent agents in displacing hydrogen in these compounds when, on dissolution of the lime, these elements appear in the soil solutions. The processes involved are not simple, but complex.

Through biological processes, carbonic, sulphuric, nitric, and humic acids are ever forming in soils, so that active hydrogen ions continuously tend to displace the cations of the base-exchange compounds. Carbonate of lime (applied) tends to neutralize these acids as they form, thereby protecting the exchangeable basic elements so long as carbonate of lime is present.

After the disappearance of added lime in a soil as carbonates, the calcium and magnesium, which have become constituents of base-exchange and other compounds, become important sources of these elements in plant nutrition. Organic matter, various calcareous silicates, calcium phosphate, and calcium sulphate are other sources. The replaceable calcium and magnesium are gradually displaced by hydrogen, resulting in the gradual development of soil acidity. The renewed exchangeable calcium and magnesium, effected through liming, also serve as regulating or buffering agents, in that they may prevent soil solutions from becoming excessively acid.

Effect of liming on soil cations. Several investigators have studied the effects of applied lime on the solubility and availability of soil potassium. MacIntire (1943) has concluded that heavy applications of any liming material may exert a repressive effect upon the solubility of the potassium in the limed soil zone, as determined by leaching or lysimeter experiments. Similar results have been obtained by Hendrick (Scot., 1930) and by Lyon and co-workers (1930). The latter investigators also found that

liming did not increase the calcium in drainage waters, although it did cause an increase in loss of magnesium.

In Tennessee, MacIntire and Sanders (1930) have demonstrated that when different liming materials were used in connection with green manure (red clover), fixation of potassium was increased, with a corresponding decrease in its loss by leaching. The explanation offered for this phenomenon is the tendency of the lime to prevent hydrolysis of the potassium-absorptive compounds.

Although lime has been found to conserve soil potassium, some investigators have found, by growth of seedlings, that supplied lime may increase "root-soluble" or available potassium, and that larger yields resulting from liming may actually cause a limed soil to lose more potassium than an unlimed soil.

Accumulation of fertilizer potassium. In addition to the beneficial effects of calcium and magnesium in conserving soil potassium, the presence of these two elements in soil base-exchange compounds also favors accumulation of potassium applied in fertilizers, as Ames and Simon (1924) have found on the Ohio soil-fertility plots. Merkle (1932) has shown that, on the Jordan Soil-fertility Plots, wherever potash fertilizer had been applied the quantity of exchangeable soil potassium has increased, except on plot 32 where a higher hydrogen-ion concentration has resulted consequent to heavy applications of sulphate of ammonia, an acid-forming fertilizer. These results indicate that the use of agricultural limes on acid soils may not only increase exchangeable calcium and magnesium, but may also increase the base-exchange property of soil colloidal compounds.

Liming and soil nitrogen. In long-continued lysimeter experiments at Ithaca, N. Y., Lyon and co-workers (1930) observed that the addition of burnt lime (CaO) to a silty-clay-loam material did not increase the total quantity of nitrogen in the drainage waters from tanks cropped with nonleguminous plants, but it did increase the loss of nitrogen by leaching from tanks cropped with legumes. In 10-year green-manure experiments on field plots on a Dunkirk silty clay loam, Lyon and Wilson (1928) found that liming increased the accumulation of soil nitrogen, as compared with unlimed plots.

In a 20-year plot experiment in Tennessee with a cowpeas–wheat rotation, Mooers (1926) found that liming caused little or no waste of nitrogen, although for a time it seemed to have accelerated losses

of nearly equal magnitude which occurred at a more uniform rate from unlimed plots.

In the long-time 5-year-rotation experiments at Wooster, Ohio, results show a tendency for limed plots to lose nitrogen faster during the third 10-year period than the unlimed plots. On most of the fertilized plots, however, liming has increased the quantity of nitrogen conserved.

Liming and micro-organisms. Decomposition (decay) of soil organic matter, nitrification, and nitrogen-fixation are adversely affected by soil acidity. It has been demonstrated that liming acid soils brings about soil conditions that are favorable to the organisms concerned in these important processes.

Nitrifying organisms cannot live in soils having acidity greater than that which varies from pH 3.5 to 4.6. The best soil reaction for these organisms varies between pH 6.5 and 7.5 (Ch. 16).

Nodule-forming bacteria (*Rhizobium*) differ in their sensitiveness to soil acidity. Some, like those of sweetclover and alfalfa, are very sensitive. This explains why liming and inoculation are both necessary for the successful growth of these legumes on strongly acid soils.

Christensen (Den., 1914-1923) and Gainey (1923) have established the fact that azotobacters, the most sensitive of all nitrogen-fixing bacteria, require soil reaction somewhat above pH 6. This sensitiveness of azotobacters to absence of basic material has suggested to Christensen how the growth of these bacteria in inoculated lime-free mannite solution may indicate the presence of basic matter in soil materials, and hence may serve to indicate the need of soils for lime.

Lime (CaO) may also aid in the control of certain crop diseases that are caused by fungi—clubroot, or finger-and-toe (*Plasmodiophora brassicae*), in cabbage and turnip fields, for example. These organisms seem to develop best in acid soils.

Lime in plant nutrition. The favorable physical, chemical, and microbiological effects of lime on acid soils may profoundly affect, directly and indirectly, root development, plant nutrition, and quality of the crop. The feeding area of a plant may be enlarged, nutrient elements may be made more available, toxic substances may be neutralized, and certain plant diseases may be controlled.

Beneficial effects of liming may extend within the crop plants

pH 9.9	Black-alkali soils (pH 9.7 to 11.0) Black-alkali weed, Alkali-purslanes, Inkweeds
pH 9.2	Limit for azotobacters (pH 9 and higher)
Strongly alkaline	
pH 8.5	Aluminum becomes soluble above pH 8.5 (toxic)
Medium alkaline	Limit of alkalinity effected by liming (about 8 pH)
pH 7.8	Above this point, insolubility of iron and manganese may result from liming and from alkalinity in alkaline—calcareous soils
Slightly alkaline	In soils with black alkali, crop plants cannot absorb phosphate nor nitrate ions at higher pH than about 7.6
pH 7.0	Sweetclover — Alfalfa — Sugar beets Red clover — Cabbages — Asparagus
Slightly acid	Barley — Sugarcane — Roses Wheat — Spinach — Tomatoes Maize — Soybeans — Flax
pH 6.2	Tobacco — Oats — Beans
Medium acid	Limit of acidity tolerance for azotobacters (pH about 6.0)
pH 5.5	Pineapples (pH 5.5 to about 6.5)
Strongly acid	Control of potato scab (pH 5.0 to 5.4) Toxic aluminum comes into solution below pH of about 5.0
pH 4.8	Blueberries, Cranberries, Rhododendrons
Very strongly acid	Abundance of fungi at pH 4.0 and below
pH 4.1	
	Limit of soil-acidity tolerance for nitrifiers (pH 3.5 to 4.6)
pH 3.4	Reaction of some peat soils (pH 3.2)

Fig. 74. Relations between soil reaction and the resulting conditions that affect soil fertility.

themselves, affecting physiological processes. Truog (1915-1930) has advanced the hypothesis that the effect of soil reaction on different kinds of plants may be explained on the basis of a physiological ratio of basic to acidic elements. For alfalfa, he found this ratio to be practically 2 to 1, calling for half of the basic elements to be absorbed as bicarbonates. In timothy, on the other hand, the ratio was reversed, being approximately 1 to 2, with no need for the entrance of cations as carbonates.

The high lime content of some plants bears a close relation to their protein content. Calcium is probably utilized as a constituent of proteins and for neutralizing by-product acids, such as oxalic acid, within the leaf cells. It also makes possible, within certain limits, the absorption and assimilation of nitrates, as well as the absorption of phosphorus.

In a study of nitrate reduction by green plants, Eckerson (1932) has found that when calcium is deficient there is early plant injury, the roots being affected first, then the stem tips.

By supplying absorbed calcium to soybeans in the form of colloidal clays that varied in acidity within tolerance range for this species, Albrecht (1931-1932) found that disease-free and apparently normal growth was determined by an adequate quantity of available calcium. A supply of calcium was required first to meet growth requirements, and then an additional quantity was necessary for nodulation.

In their study of soil-crop relations on the Pennsylvania plots, White and Holben (1930) have obtained results that would indicate that acid soils are unable, even with liberal use of fertilizers, to produce good-quality clover-and-timothy hay.

The problem of liming. In harmony with the principle of soil fertility (see Index), the problem of liming soils may be stated as follows: To determine the quantity of lime to apply per acre sufficient to create proper mediums for crop plants so as to enable them to best obtain their nutrient requirements.

The practical and scientific relations between soil reaction and the resulting conditions that affect soil fertility are summarized in Figure 74.

The fact that general farm crops, including alfalfa, red clover, sugar beets, and barley, may be satisfactorily grown on slightly acid soils would indicate an economic solution of the liming problem, in that it is not necessary to neutralize the total acidity, but

rather to bring the reaction of acid soils within the range of slight acidity, or between pH 6 and about 6.8. Fields devoted to alfalfa, sweetclover, cabbages, and turnips, however, may be given special lime treatment. And where soil conditions or prevalence of fungous diseases require it, potato and tobacco soils may be limed less in order to maintain proper acidity for the control of scab and black root rot. The proper acidity range for potatoes, as Martin (1930) has indicated, is from pH 5 to 5.4; and for tobacco, according to Morgan and co-workers (1929) and Doran (1931), the acidity range is from pH 4.8 to 5.6.

Acidity of about pH 5 and lower brings toxic aluminum into solution, increases active soil acidity, and renders phosphorus less available (Ch. 16). In eastern Kansas, Sewell and Perkins (1928) found that acid soils which contained large quantities of aluminum leachable with 0.05 normal hydrochloric acid generally produced the lowest yields of Indian corn and alfalfa.

From a study of soil constituents that inhibit the action of plant toxins, Truog and Sykora (1917) have concluded that most arable soils seem to be so constituted that, through liming and proper drainage, they may prevent entirely, or to a large degree, any injury by toxins that may be present or that may form in them.

Injury from overliming. Early agricultural writings and recent literature contain references to depressed crop growth resulting from overliming. It is common experience that in time overlimed soils will correct themselves, so far as conditions for normal growth are concerned. Depressed growth may result from causes other than high pH value, or alkalinity.

The danger of making acid soils alkaline may lie in the reversion action of lime on available iron and manganese, causing lime-induced chlorosis in many plants. Lettuce, cucumbers, cantaloups, strawberries, and sweetpotatoes have been found to develop chlorosis as the result of liming. On some heavily limed soils, snap beans and soybeans have developed chlorosis as a result of manganese deficiency. For soils of the Atlantic Coastal Plain, Willis (1929) has advised against the reduction of soil acidity beyond pH 6.4 or 6.5, to avoid chlorosis resulting from manganese deficiency (see Index).

The reversion action of lime on available iron and manganese suggests a probable relation between available iron and manganese in alkaline soils, particularly those in regions of limited rain-

fall. Kellogg (1931) has suggested magnesium as a possible key to the phosphorus problem of certain semiarid soils of North Dakota, owing to the tendency of calcium carbonate to depress the availability of magnesium.

Bobko and co-workers (Russ., 1927) and Tacke (Ger., 1930) have cautioned against overliming acid peat soils, owing to the consequent production of ammonia from intensified biological processes, and absorption of available nitrogen by increased number of microorganisms (Ch. 5).

Meyer (1932) discovered that one of the immediate effects of overliming certain acid soils was a greatly increased iron content of the soil solutions, owing to a temporary increase in carbon dioxide (carbonic acid) which lowered the pH value of the soil solutions, thus favoring solubility of iron. When conditions came to equilibrium, solubility of the iron decreased to a point favorable for normal growth. Added lime may also be responsible for toxic aluminum, and for making boron unavailable in some soils. Midgley (1940) found that superphosphate, manure, and boron-containing materials corrected such injury. Borax (from 10 to 40 lb. per acre) proved to be beneficial for alfalfa.

It may be possible by adding too liberal quantities of agricultural lime to render unavailable the magnesium and potassium of soils that do not contain much exchangeable basic elements. Also, liming may temporarily disturb phosphate nutrition.

Fruit trees and soil reaction. Continual use of acid-forming fertilizers and sulphur in spray materials, as for fruit trees, may result in the development of excessive acidity in orchard soils, with injurious results.

In certain citrous groves in Florida, Fudge (1930) has noted severe injury (chlorosis) to trees in places where considerable lime had been used. Less injury was observed in places where the soils contained appreciable quantities of organic matter. According to J. P. Bennett (1931), many orchard and ornamental trees in California are injured by excessive lime content of soils causing chlorosis. A temporary or emergency remedy consists in applying iron in suitable soluble form and in sufficient quantity directly to the plant (see Index).

Materials for liming. The forms of agricultural limes listed at the top of p. 321 may be used in correcting soil acidity.

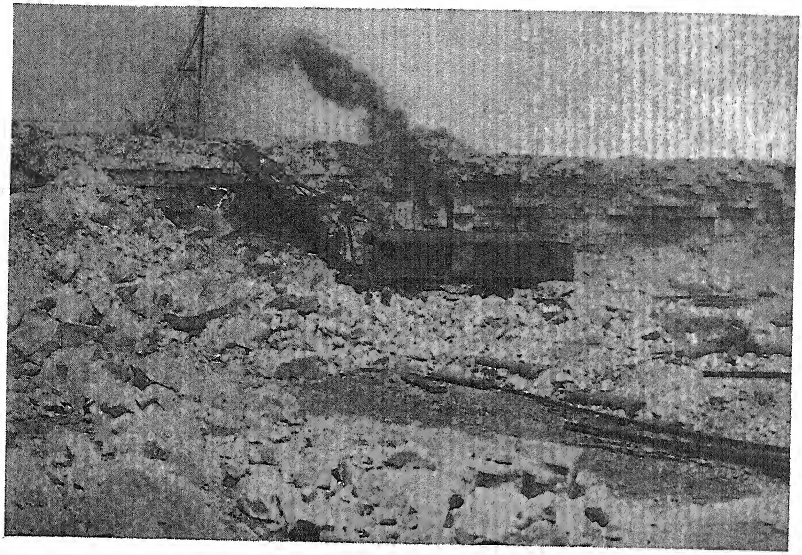

Fig. 75. A limestone quarry, a source of agricultural lime.

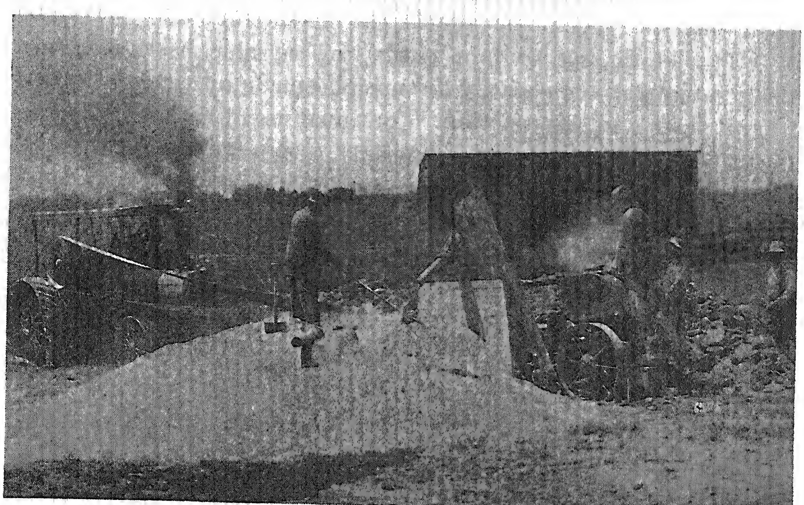

Fig. 76. Pulverizing limestone on a farm in a limestone country.

1. **Calcium oxide,** (CaO), which is quicklime, burnt lime, lump lime, builders' lime, caustic lime.

2. **Calcium hydrate,** $Ca(OH)_2$, which is hydrated lime, water-slaked lime, agricultural lime.

3. **Calcium carbonates,** ($CaCO_3$), which includes pulverized limestone, agricultural limestone, precipitated lime, waste lime, air-slaked lime, ground shells, marble "dust," marl, and natural chalk (Figs. 75 and 76).

4. **Calcium-magnesium carbonates,** including dolomitic limestone, dolomite, pulverized limestone, agricultural lime, air-slaked lime.

5. **Calcium silicates,** such as blast-furnace slag, basic slag.

Calcium sulphate, $CaSO_4 \cdot 2H_2O$ (gypsum, or land plaster), is another calcium compound. Although this material may prove to be of value to some crops, it has no value for neutralizing soil acidity, owing to its strong-acid radical, or anion (SO_4^{--}). Wood ashes also have liming value, but coal ashes do not.

Liming materials should consist of at least 80 percent of calcium carbonate or its equivalent, and they should be finely ground or pulverized. Materials like limestone, shells, and marl should be sufficiently pulverized so that about 60 percent of the material will pass through a 60-mesh sieve.[1]

Effectiveness of agricultural limes is determined by the chemical nature of the material, concentration or purity, fineness, and thoroughness in which they are incorporated into soils. On the chemical basis, the order in which the five groups of lime materials are named indicates their quickness of action. Pierre (1930) has demonstrated that the rate of reaction of the various forms of lime with acid soil materials increases with hydrogen-ion concentration and the avidity of the soil acids.

Comparative values of lime materials. On the basis of the neutralizing value of pure materials, comparative values of carbonate, hydrate, and oxide may be expressed as follows: 2,000 pounds of limestone = 1,480 pounds of hydrated lime = 1,120 pounds of burnt lime.

Soon after a 1,120-pound application of burnt lime (CaO) is added to a soil, it becomes the equivalent of 2,000 pounds of calcium carbonate. This also holds true for a 1,480-pound application of hydrated lime.

The content of calcium carbonate or its equivalent is commonly taken as the basis for comparative neutralizing values of suitable agricultural limes.

[1] A 60-mesh sieve has 60 openings per linear inch, measured from center of wires.

Lime-magnesia ratio. At one time magnesian liming materials were discriminated against because of their magnesium content. This prejudice had its origin in some work done by Loew (Ger., 1892) and Loew and May (1901) regarding the relation of lime and magnesia to plant growth, from which the following principal conclusions were drawn: (1) Plants require a ratio of soluble lime (CaO) to soluble magnesia (MgO) of about 5 to 4, by molecular weight, for best germination and growth; (2) the quantity of calcium must exceed that of magnesium; (3) if magnesium exceeds the calcium, plant injury results; and (4) a great excess of calcium over magnesium causes development of starvation symptoms. Other investigators have failed to obtain evidence to support this ratio theory.

On some soils, crops have failed to grow or have developed chlorosis as the result of a deficiency of magnesium (Ch. 9). Other soils, especially some which have developed from materials originating from serpentine rocks (hydrous magnesium silicate), have been found to contain excessive or toxic quantities of magnesium. Still other soils contain excessive quantities of calcium carbonate; this excess causes the depression of available magnesium. Although these conditions have been found, no harmful effects are known to have resulted from the use of magnesian or dolomitic limestone on acid soils. Usually, pound for pound, dolomitic limestone has proved to be as effective in neutralizing acidity as pure limestone, even showing a slight advantage in some comparative tests. The use of magnesian limestone on some soils has an important bearing on plant nutrition, in that deficient magnesium may be supplied.

From lysimeter results, MacIntire and Shaw (1930) have concluded that, in humid regions, toxic or excessive magnesium cannot result from the use of dolomitic limestone, for the reason that the loss of added magnesium by leaching exceeds that of added calcium.

Quicklime v. lime carbonate. Owing to its caustic properties, one might infer, and certain chemical analyses seem to indicate, that calcium oxide would have a destructive action on soil organic matter. This, however, is not the case, as White and Holben (1924) have shown by their investigation of the soil on some of the Jordan Soil-fertility Plots in Pennsylvania. Here, after 40 years,

no evidence could be found of quicklime burning out soil organic matter. Quicklime soon becomes carbonates when added to soils.

When and how to lime. Farmers' convenience commonly determines the time when lime materials are applied. A common rule to follow is this: Apply lime and mix it with the soil material before the crop that is to be especially benefited is planted.

Application of agricultural lime to fall-plowed land is an excel-

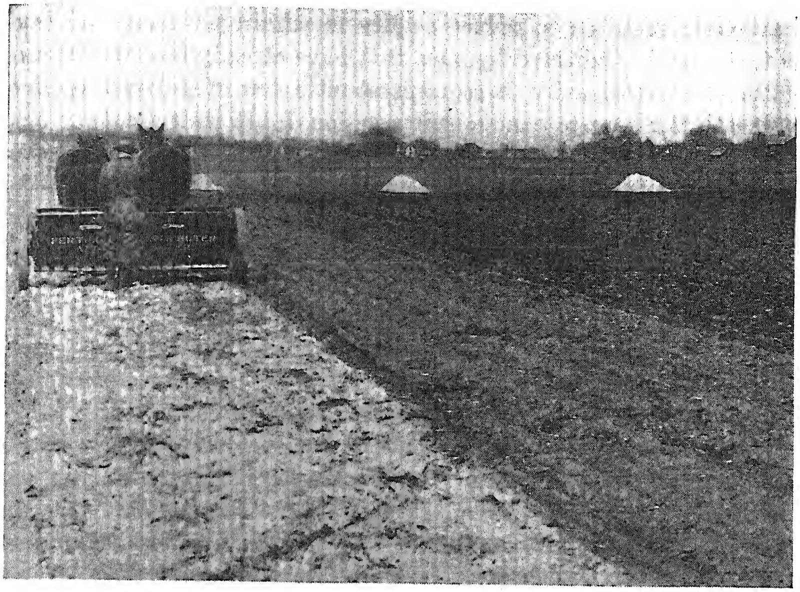

Fig. 77. Applying pulverized limestone with a lime distributor.

lent practice. Lime is commonly applied on rough plowed land or after a single harrowing, and incorporated into soils through subsequent cultivation.

Lime materials may be spread by hand-shoveling from a wagon or from small piles, but they can be applied most conveniently by lime-distributing implements (Fig. 77).

Top-dressing with lime. Although agricultural limes, when broadcast, produce best results when they are thoroughly mixed with surface soil materials, one has to forego the mixing process when liming pastures, lawns, and other grassed areas, and apply the lime as top-dressing instead. For this purpose, finely divided materials such as hydrated lime, air-slaked lime, high-grade marl,

and finely pulverized limestone may be used. Hydrated lime in moderate annual applications is commonly used on lawns.

The best way to lime land intended for grass is to incorporate the lime material during the preparation of the seed bed. But if the grass is already established, top-dressing is the only alternative.

How much lime to apply. The quantity of lime material to apply to an acre is determined by the degree of soil acidity, kind of soil, and kind of material. The approximate quantity of lime carbonate required to reduce acidity to within pH range of from 6 to 7 may be indicated by tests that have already been mentioned (Ch. 16). Ordinarily, it requires about 1 ton of pulverized limestone to the acre to change soil reaction 1 pH in a strongly acid sandy loam to a depth of about 5 or 6 inches; and in a heavy loam, about 1.5 tons are required.

On very acid soils, a 2-ton initial application of finely ground limestone may be regarded as an adequate treatment for general crops. Many acid loams and silt loams that vary from strong to medium acid (pH 4.8 to 5.6) have been observed to respond to 2- and 1-ton applications of pulverized limestone and hydrated lime, respectively, even in growing alfalfa (Fig. 71), and have continued to respond to these initial applications after 10 or 15 years.

How often to lime. When once the proper soil reaction of an acid soil has been obtained, its maintenance may require applications of some lime material at more or less regular intervals, in order to maintain soil conditions that crop plants require. Some farmers in the older agricultural districts of the United States have made it a practice to apply from 500 to 800 pounds of hydrated lime or about 1,000 pounds of lime carbonate an acre once in 4, 5, or 6 years, as conditions may demand. On many of these fields the acidity has been found to vary from about pH 5.8 to 6.3. Other farmers have applied lime, after the initial application, from time to time as conditions or tests indicate the need for lime.

On loams and silt loams, one application sufficient to meet initial requirements for general farm crops may last for from 10 to 15 or more years, after which moderate quantities applied at intervals seem best.

In considering the loss of calcium in drainage waters, as shown by the use of lysimeters, cognizance should be taken of the fact that soil depths of from 3 to 3.5 and more feet are involved. The quantity of calcium required to replace the annual loss from the

surface or tilled layer of different soils, to a depth of 8 inches, has not been determined.

Owing to the absorption power of soil materials, the calcium and magnesium applied in rational liming soon become fixed almost entirely in the upper layers. Wilson (1918) made a study of the translocation of calcium in a rather acid clayey-silt-loam material, and found that applications of either burnt lime or ground limestone did not result in any downward movement of calcium by percolation, nor did calcium move upward by diffusion when the same materials were placed at the bottom of the pots.

In Indiana, Conner and co-workers (1928) found that an application of as much as 12 tons of calcium limestone per acre on two soils classed as *Clermont silt loam* and *Newton fine sandy loam* had affected the acidity only slightly below a depth of 6 inches (the slight effect was probably due to difference in the depth of plowing), and the soil reaction was not at all affected below a depth of 12 inches. These investigations were made the seventh year after the experiment fields were established.

In a long-cropped (200 years) Manor loam in Maryland, which had received 6 tons of burnt lime an acre in 42 years, the soil material to a depth of 18 inches was found to be very slightly acid. To the same depth in virgin soils the soil materials were strongly acid.

Fractional neutralization of soil acidity. McCool (1927) has suggested the possibility of increasing crop yields by applying from 300 to 500 pounds of limestone per acre in the drillrow with sweetclover, alfalfa, or red clover seeds. In testing such drillrow application, Albrecht and Poirot (1930) have successfully established red clover and sweetclover on a Gerald silt loam in Missouri, having acidity of pH 5 (depth, 0 to 7 in.), with the use of pulverized limestone (combined with inoculated soil material) drilled in with the seed at the rate of 300 pounds an acre.

Calcium added by water and fertilizers. The fact has been mentioned that low level lands that are flooded annually by waters which drain from limestone districts are usually not acid, owing to absorption of calcium by the soils. Through continual use of hard water for watering or irrigation, considerable quantities of calcium may be absorbed by soils. Some vegetable growers use large quantities of hard water for overhead or spray irrigation. Soil reaction clearly indicates that through such a practice slight

acidity may be completely neutralized, necessitating the occasional use of acid-forming fertilizers in order to keep the soil reaction within the range of from about pH 6.1 to 6.8.

A number of fertilizers contain calcium or both calcium and magnesium in the form of compounds of phosphorus and nitrogen, and these basic elements also occur as impurities in superphosphate and potash fertilizers. These basic elements, in part at least, are absorbed by the soil materials with beneficial results.

Liming in agriculture. Experiments and field demonstrations the world over have established the fact that liming is the first step in the improvement of most acid soils. In many places it has been shown that liming and inoculation are two essential treatments whereby acid soils may be made fertile for crops like alfalfa, sweetclover, and red clover. Liming may be regarded principally as a means for conditioning acid soils for economical and profitable production of crops through good tillage, rational fertilization, and proper rotation of crops.

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REVIEW QUESTIONS

1. Take into consideration soil reaction and sketch its development.
2. Discuss the importance of calcium in the improvement of acid soils through liming.

3. Does a high degree of fertility of a soil depend on the presence of lime carbonate in the soil? Explain.
4. What is the effect of agricultural lime on soil potassium, calcium, magnesium, and nitrogen? Explain why.
5. Discuss the physiological effects of agricultural limes when applied to acid soils.
6. What economic principle should guide in the use of agricultural lime? Illustrate.
7. Explain why injury to a soil may result from overliming.
8. Explain the difference in the quickness of action of the different forms of agricultural limes.
9. Explain why in most soils the theory of the lime-magnesia ratio does not hold. What significance have the facts concerned in relation to the use of dolomitic limestone for soil improvement?
10. Explain why "lime" that is added to acid soils may be regarded as a regulator of soil fertility.
11. Discuss the economic use of agricultural lime in farming.
12. Is there any danger in using dolomitic limestone on acid soils?
13. Discuss the lime problem on calcareous soils of dry regions.
14. Explain the function of calcium and magnesium in soil improvement.

CHAPTER 18

SOIL ORGANIC MATTER AND SOIL FERTILITY

The organic matter in soils originates from green plants, animals, and soil micro-organisms. Some of this material is undecomposed, some (humus compounds) is very resistant to decomposition, and certain organic substances are intermediary products formed in decay of original residues, while other materials are products that have been synthesized by soil micro-organisms. Inasmuch as plant residues constitute the principal source, much of the soil organic matter is composed of cellulose, lignin, protein compounds, waxes, oils, and other plant constituents.

The quantity and kind of organic matter in soils are determined largely by the activity of micro-organisms; and in turn, the activity of micro-organisms is affected by soil moisture, soil aëration, temperature, soil acidity and alkalinity, and the supply of energy and nutrients (Ch. 5).

The quantity of organic matter contained in soils varies widely, from comparatively small percentages in sandy to more than 70 percent in peat soils. By far the greater part of the organic materials in soils occurs in the topsoils. In the soils of the United States, the average content is about 2 percent, as compared with about 0.8 percent in the subsoils. Shades of color roughly indicate the comparative quantities of organic matter in soils, owing to the property of the dark-colored colloidal humus compounds to coat the mineral particles.

Soil types and organic matter. In relation to the broad or world groups of soils, the quantity of organic matter contained in the soils represented is determined by the character of these soils. According to Marbut (1931), their character is determined by the vegetation, kind of mineral soil constituents, environment in which soil development takes place, and stage of soil development. Striking differences may be observed in soils classed as Desert, Chestnut (plains), Chernozem (black, grasslands), Podzol (gray forest), Gray-Brown Podzolic (forest), and in soils developed under condi-

tions of permanent saturation. The principal differences in organic matter between forest soils and those classed as Prairie and Chernozem are to be found in the character of the organic matter and in its solum distribution. With reference to these soils, the following two facts have considerable significance: (1) "mild" or nonacid humus is less soluble than acid humus; and (2) organic matter accumulates much faster under grass than under forest cover.

Importance of organic matter. The importance of soil organic matter in relation to crop growth has long been recognized. The early use of manure in ancient times gave rise to the idea that plants fed on substances that corresponded with their own nature. In later years, following the Renaissance, this belief was greatly strengthened by chemical analyses which showed that soil "humus" contained nitrogen, the most important constituent of plants. Hence the rise of the humus theory of plant nutrition, which was strongly supported by Thaer (Ger. 1809).

In 1804, De Saussure, of the Geneva school, regarded soil organic matter, or "humus," as the principal source of the nitrogen of plants. But as this investigator was the first to observe the stimulation of plants by ammonium salts, he suggested atmospheric ammonia as a possible source of plant nitrogen. The year 1840 marks the end of the humus theory of plant nutrition, because Liebig's inference that plants utilized simple mineral and gaseous substances was accepted as the proper basis of inquiry into plant nutrition.

The importance of organic matter in relation to soil fertility is generally recognized. Its functions may be classed as physical, chemical, biological, biochemical, and nutritional.

Physical relations of soil organic matter. The importance of organic matter in relation to physical properties of soils was recognized by Davy (Eng.) in 1813, and particularly by Schübler (Ger.) in 1838; but owing to the emphasis that was placed on chemistry following 1840, this line of inquiry was forced into the background until it was revived during the period from 1878 to 1898, when attention was again directed to soil physics (Ch. 3).

The physical effects of organic matter on soils are very complex, owing to the complex nature of the two materials concerned. However, the effects have qualitative significance in connection with

weight, cohesion, structure, porosity, color, temperature, and tilth (Ch. 3).

Raw or fibrous organic materials separate soil clods, and thereby render soils more tillable. This may be demonstrated by the favorable effects of timothy and redtop roots, as may be observed in developing a seed bed on prime sod on a heavy or clayey soil. The mechanical effects produced improve both drainage and aëration.

The importance of organic matter and humus in relation to water-retaining power of soils, development of structure, and to other soil properties has been discussed in Chapters 2 and 3.

Analyses have shown that colloidal organic and inorganic soil materials are intimately associated, indicating a very close relationship between humus compounds and physicochemical soil properties like base-exchange and the property of humus materials in acting as a protective coating to mineral soil particles.

Chemical importance of organic matter. Chemically, soil organic materials function in three important ways: (1) They constitute direct sources of nitrogen and other plant nutrients; (2) they aid in rendering available soil calcium, magnesium, iron, and phosphorus; and (3) humic colloidal substances function in base-exchange and other soil reactions (Ch. 4).

In reference to plant nutrition, organic materials act directly and indirectly, for it has been demonstrated that sugars can be assimilated by higher plants. Bottomley (Eng., 1914-1920), finding that small quantities of organic substances extracted from soil materials stimulated plant growth, has concluded that vitamin-like substances, which he has named "auximones," are essential to the life and reproduction of green plants. Results obtained by Breazeale (1927) seem to indicate that plants require small quantities of certain soil organic substances for normal growth, and that the source of these vitamin-like substances is vegetable matter.

Several organic substances have been found to stimulate plant growth—including bios, yeast water, plant extracts, organic extracts, peat extracts, soil extracts, and auximones—indicating the importance of organic substances in plant nutrition.

Burk and co-workers (1931) have obtained evidence that natural humic acids of soils increase growth of various higher and lower plants principally, if not entirely, by virtue of the iron contained in these humic acids.

Certain organic substances may prove to be toxic to crop plants.

For example, Neidig and Snyder (1928) have concluded that low productivity of certain recently cleared coniferous timber land in Idaho is caused by resinous substances which are toxic to crop plants and which may for years retard the activity of nitrifying organisms.

Soil organic matter also functions as a source of carbon dioxide for higher plants. Also, trace-essential elements that are commonly present in plants probably play an important part in plant nutrition as they are rendered available through decomposition.

In decomposition of nitrogenous organic matter, nitrogen and mineral elements are liberated, and acids that are produced act on the mineral soil particles and render mineral elements available.

Nitrogenous organic materials bear a most important relation to ammonification and nitrification (Ch. 5).

Meyer (1931) has pointed out that in the southeastern States the problem of available soil phosphorus is closely related to the problem of organic matter, in that the most important function of organic substances is in keeping the soil phosphates sufficiently soluble for plant growth. The problem of soil fertility in these States concerns not only the use of fertilizers, but the use of green manure as well.

In relation to soil fertility, organic colloidal compounds serve in double capacity. They fix added calcium, magnesium, potassium, and phosphorus, and in turn, they gradually give up these elements as nutrients. Furthermore, organic matter and humus provide a more or less constant supply of nutrient elements, because of comparatively slow decay and chemical changes.

Organic matter and base-exchange. According to Stoklasa (Czech., 1929), Du-Toit and Page (Eng., 1930), McGeorge (1930-1931), and Waksman (1931), much of the material that constitutes humus is derived from lignin of plant residues. It has been found that lignin and lignin-like substances have base-exchange properties (Fig. 78). Considering the fact that these compounds are present in practically all plants, McGeorge (1931) has inferred that raw plant materials possess the property of base-exchange. This he has found true with respect to raw alfalfa material (not roots). These facts indicate that greater significance is to be attached to green-manuring, in that the raw plant materials added to soils function as base-exchange compounds and increase the supply of available nutrients.

From his inquiry into base-exchange properties of soil organic matter, Mitchell (1932) has obtained results which indicate that at least two different classes of materials are responsible for base-exchange properties of soil organic matter: namely, "lignin-humus" and hemicellulose-containing substances, the former being the more important.

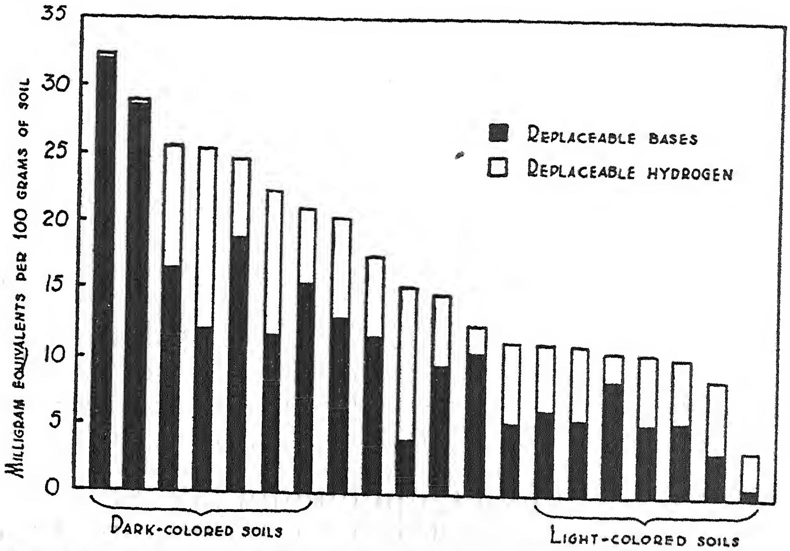

Fig. 78. Capacity of dark-colored soils of northern Illinois for holding basic elements, compared with light-colored soils of the southern part of the State. (Ill. Agr. Expt. Sta.)

As a buffering agent, organic matter functions as do inorganic base-exchange materials; and soil ion-exchange capacity may be favorably influenced more by organic matter than by clay (Ch. 6).

Biological importance of organic matter. The biological and biochemical importance of soil organic materials is indicated by the fact that they influence the growth and development of soil micro-organisms by effecting a more favorable physicochemical environment, and by providing them with sources of energy and suitable nutrients. In well-drained and well-cultivated soils, the micro-organisms concerned are principally fungi and aërobic heterotrophic bacteria which decompose organic materials in order to obtain their requirements. But in doing so they liberate and render available nitrogen and other elements that are essential in plant nutrition.

In ammonification, protein and other nitrogenous compounds constitute the sources of ammonia which, in turn, becomes the raw material in nitrification. Accordingly, when other conditions are favorable, the greater the content of organic matter in soils, the more abundant is its bacterial population and the more rapidly will nitrification take place.

The changes that plant and animal residues undergo in soils through decay take the general direction toward simple compounds like carbon dioxide, water, ammonia, hydrogen sulphide, and simple compounds of mineral elements—directly opposite to the changes that take place in living plant bodies. The complex organic substances that resist the action of micro-organisms constitute the principal source of soil humus (Fig. 30).

Nodule-forming or symbiotic bacteria obtain their energy from carbohydrates that are supplied by the host plants. However, it has been found that carbonaceous substances, including carbohydrates, certain organic acids, and alkaloids, stimulate nodule production on legumes.

Nonsymbiotic nitrogen-fixing bacteria obtain their energy principally from carbohydrates and similar compounds and from salts of organic acids.

The addition of organic matter to soils causes an increase in the number of micro-organisms, some of which effect decomposition, some utilize the products that result from decay, while others attack the living or dead cells of the organisms that effect decomposition. The nature of the organic matter added may profoundly affect the development of the soil microflora. For example, materials rich in cellulose and poor in protein, like straw, stimulate development of fungi and cellulose-decomposing bacteria, whereas materials that contain soluble sugar stimulate the development of other bacteria.

According to Waksman and Starkey (1924), materials such as crop residues, green manure, stable manure, and organic fertilizers, which consist of a variety of organic substances, stimulate various groups of soil micro-organisms, such as actinomycetes, other fungi, and bacteria. The greater the protein content of the materials added, the greater is the development of bacteria.

Added organic materials may cause injury. Inasmuch as soil micro-organisms require nitrogen, phosphorus, and other elements for the production of their cell protoplasm, rapid development of

the soil microflora, resulting from the addition of carbon-rich or energy-producing material, may result in competition of crop plants with fungi and bacteria for available soil nitrogen. Such competition may develop when a crop is planted soon after a large quantity of straw or non-nitrogenous green manure is turned under. Under these conditions the crop usually suffers for want of available nitrogen, as may be indicated by stunted growth and yellowing of the foliage. An immediate remedy may consist in applying a liberal quantity of readily soluble nitrogenous fertilizer like nitrate.

This phenomenon of nitrogen starvation was first observed by Kruger and Schneidewind (Ger., 1901), and subsequently by several other investigators, although Wagner (Ger.) had previously observed (1895) that unrotted dung "destroyed" soil nitrates and reduced crop yield. The condition of minimum nitrate for crop plants develops quicker and continues longer in soils that are deficient in nitrogen than in soils that are well supplied with this element. Strong depressing effects on crop plants do not follow the application of materials that contain appreciable quantities of nitrogen like stable manure and legume residues.

Organic matter in orchards. The value of organic matter in orchard soils is becoming more generally recognized. Whether in citrous groves, deciduous orchards, or pecan groves, it has been found that best results depend in a large measure on systems of orchard management that include the growing of cover crops, the use of stable manure, or the turning under of sod at intervals of 4 or 6 years. In cultivated orchards cover crops are especially valuable in conserving soil nitrogen and in supplying organic matter (see Index).

Investigators have found that solubility of soil calcium, magnesium, iron, and phosphorus may be measurably increased through the addition of green manures, stable manures, and extracts of these materials. Increase in solubility of these constituents results in part from the action of inorganic salts contained in the organic materials and their extracts, and in part from the solvent action of the soluble organic compounds formed during decomposition. In alkaline soils, organic substances like manure and green manure are valuable sources of carbon dioxide, which is so important in the fertility of such soils.

Maintenance of soil organic matter. Whatever interpretation may be given the expression "maintenance of soil organic matter," its meaning concerns soils that have been brought under cultivation. The basis of the maintenance concept has never been determined quantitatively, probably because the concept is one of relationship or relativity. Logically, the relation is between soil organic matter and economical soil productivity. In other words, *maintenance of organic matter* simply refers to soil organic matter as one of the important factors that determine soil fertility.

It is a well-known fact that many soils have suffered enormous losses of organic matter, particularly during the first few years of cultivation. During the years of rapid decay of organic matter, maximum crop yields were usually obtained. The principal cause of low yields on many soils is a deficiency of organic matter, owing to an originally low content or to exhaustive cropping.

Snyder (1897) found that continual cropping with wheat for 8 years in Minnesota caused a loss of over 21 percent of the total quantity of soil nitrogen, above that used by the crops. This is equivalent to an annual loss of 175 pounds of nitrogen or about 3,500 pounds of organic matter per acre. Shutt (1910), Alway and Trumbull (1910), Swanson (1915), and Lipman and Blair (1921) have obtained similar data for Canadian prairie soils, in dry farming in Kansas, and in intensive cropping in New Jersey, respectively. In their study of the silt-loam soils of the eastern part of Washington (rainfall from 15 to 21.5 inches), Sievers and Holtz (1922) have found losses of 22.1 percent of nitrogen and 34.5 percent of organic matter during 39 years of cropping.

At Rothamsted (Eng.) an uncropped soil left exposed to the weather lost from the surface 9-inch layer, 1,124 pounds of nitrogen per acre during the period 1870 to 1916, which was a reduction in percentage of nitrogen from 0.146 percent (initial) to 0.099 percent.

The problem of soil organic matter. Improvement of many soils that have been depleted of organic matter usually proves to be rather expensive, owing to the fact that their producing power had been allowed to decline to a degree that makes it difficult to grow green-manuring or soil-improvement crops without special treatment or expensive fertilization, or both.

Inasmuch as the carbon-nitrogen ratio in soils is usually about 10 or 12 to 1, it follows that the problem of organic matter is also

the problem of soil nitrogen. In general, the percentage of nitrogen varies as the organic matter, and the quantity of nitrogen cannot be materially increased in soils without increasing the quantity of nitrogenous organic matter. Accordingly, it may be said that, under favorable conditions, any system of cropping or soil management that provides an adequate supply of organic matter to maintain soil productivity also provides an adequate supply of nitrogen for the crops concerned.

Any endeavor to maintain in a given soil a supply of organic matter far in excess of what is required for yields which that soil is able to produce may mean an enormous waste of human effort and important soil constituents. In a given region or on a particular farm, a system of cropping or soil management that is economically productive may have in it the best solution of the organic-matter problem for the soils concerned.

Organic matter in arid soils. Owing to scanty vegetation and extremely rapid decomposition, the original content of organic matter in arid soils is very low. Thus, a common problem in irrigation farming is that of providing adequate organic matter. Burgess (1929) has found, however, that it is not economical to increase permanently the supply of organic matter in irrigated soils, as in soils of humid regions, to any great degree.

The common sources of soil organic matter in irrigation farming are the same as in farming in humid regions, except that alfalfa constitutes a most important crop in producing soil organic matter. A problem that may attend the use of milo, kafir, and hegari for green-manuring crops is that of depression of soil nitrates (Ch. 5).

Organic matter in dry farming. Soils under dry-farming conditions have suffered enormous losses of organic matter. According to Russell (1929), soils in dry-farming sections of Nebraska have lost from 6.5 to 56 percent of their original organic matter in from 3 to 60 years of cropping. Here the problem of soil organic matter is more complicated than in arid (irrigation) and humid regions, owing to the limited sources of water. An increase in available nitrogen, effected through green-manuring with a legume or by alfalfa sod, may increase crop growth, but with consequent harmful reduction of the supply of soil moisture. This accounts for the tendency of crops to "fire" when following alfalfa (Ch. 12). On the other hand, the addition of cellulose-rich materials may cause a deficiency of available soil nitrogen. A solution

of this problem may consist in supplementing the use of nonleguminous materials with suitable nitrogen fertilizers.

Sources of organic matter in cropping. The principal sources of soil organic matter in practical farming include crop residues, stable manures, green manures, and certain commercial fertilizers.

Crop residues consist mainly of roots, stubble, straw, and stalks. By weight, more than half of the total substance of many plants consists of underground roots. This form of organic matter is thoroughly distributed in soils. Stoklasa (Czech., 1926) has given the following quantities of stubble and roots and carbon that are left in the fields after harvest:

STUBBLE AND ROOTS AND CARBON LEFT PER HECTARE AND ACRE

Crop	Dry Plant Substance		Carbon Content	Total Quantity of Carbon	
	Kg per ha	*Lb. per acre*	*Percent*	*Kg per ha*	*Lb. per acre*
Oats	4,285	3,823	49.1	2,104	1,877
Wheat	4,316	3,850	49.7	2,145	1,914
Rye	4,328	3,861	44.8	1,939	1,730
Barley	4,894	4,366	50.6	2,450	2,186
Red clover	9,163	8,174	46.9	4,297	3,833
Alfalfa (lucerne)	11,432	10,200	45.2	5,167	4,610

Although considerable, the quantities of residue ordinarily left by cereal crops are not sufficient to maintain soil organic matter. The data in the table show clearly the importance of clover and alfalfa in crop rotations.

It has already been pointed out that plant residues do not have the same value as organic matter, for the reason that some are rich in cellulose and poor in nitrogen, whereas others, like legume materials, are comparatively rich in nitrogen. The former may cause a deficiency of available nitrogen, whereas the latter have proved to be valuable sources of available nitrogen.

White's investigation (1931) of the soil of the Jordan Soil-fertility Plots of Pennsylvania, on which a 4-year rotation of maize, oats, wheat, and hay (clover and timothy) is conducted, has resulted in the following information regarding the relation between crop residues and the quantity of organic matter in cultivated soils in humid regions:

1. It is exceedingly difficult to increase the content of organic matter and nitrogen by crop residues in most well-drained cropped soils.
2. Ordinarily, crop residues that decompose rapidly when incorporated

into soils add but little to the total content of soil organic matter. Where a slow accumulation does occur, measurable quantities of increase can be detected by chemical analysis only after a period of years.

3. Under a proper system of cropping, a gain of soil organic matter takes place during the period in which a soil is left undisturbed in legume, grass, or sod; but this gain is soon lost on cultivation, resulting in a balance or equilibrium between the organic matter gained and lost. Thus the addition of organic matter to cropped soils counterbalances the gradual diminution that results from cultivation.

4. As a result of increased quantities of crop residues that result from improved methods and rational fertilization, crop yields may be increased, but the quantity of soil organic matter may remain fairly constant.

Stable manures differ greatly in organic constitution and chemical composition, and they encourage the development of both fungi and bacteria in soils. Investigations have shown that systematic applications of manure, combined with rotation of small grains, have not effected any pronounced increases in organic matter of depleted soils. A more or less definite level of organic matter ultimately becomes established in soils, being determined largely by systems of cropping.

The displacement of horses by motor vehicles in urban commercial centers, and the consequent difficulty of obtaining manure has forced many market gardeners and truck growers near these centers to learn five important facts regarding soil organic matter; these are: (1) heavy application of manure will abundantly supply the necessary soil organic matter; (2) commercial fertilizers cannot be substituted for manure; (3) best results from chemical fertilizers can be obtained only when soils are adequately supplied with organic matter; (4) if the manure supply is limited and an intensive succession of crops is practiced, the organic-matter problem may be solved by supplementing lighter applications of manure with suitable fertilizers; and (5) if manure is not available and intensive succession of crops is not practiced, adequate organic matter may be supplied by legumes and cover crops.

Soil organic matter and climate. Of the factors that affect accumulation, conservation, and reduction of soil organic matter, climate (including temperature and rainfall) is of major importance. Jenny (1930) has found that, in regions of similar moisture conditions, the quantities of soil nitrogen and organic matter decrease with increasing temperature from north to south; while with increasing rainfall, in regions of similar temperature condi-

tions and under cover of grass vegetation, the quantities of these two soil constituents increase.

Soil organic matter and liming. Although liming acid soils favors the development and activity of soil micro-organisms, it does not follow that liming will necessarily result in greater losses of soil organic matter and nitrogen (Ch. 17). Wheeler and co-workers (1899) found that air-slaked lime had effected an increase in organic matter in a soil on grassed plots, as compared with unlimed plots. Lipman and Blair (1913) have reported a greater loss of nitrogen from limed than from unlimed soil, whereas Potter and Snyder (1916) found that liming resulted in a gain of soil nitrogen.

On the long-continued Jordan Soil-fertility Plots, White and Holben (1924) found, at the end of 40 years, that both burnt lime and carbonate of lime had conserved soil organic matter and nitrogen, as compared with unlimed plots. White (1927) has concluded from his studies of the Pennsylvania plots that when liming is practiced in conjunction with the use of manure or complete commercial fertilizers, the increased yields will supply additional crop residues (roots and stubble) sufficient at least to counterbalance that which is destroyed as a result of the increased activity of micro-organisms.

GREEN-MANURING

Green-manuring may be defined as incorporating into soils green or more or less mature crops that have been sown for this purpose. A second crop of alfalfa or clover may be turned under as green manure or as a secondary use of the crop. Cover crops are commonly used for green-manuring.

Green-manuring an ancient practice. Doubtless primitive husbandmen knew the value of green plant materials in crop production at a very early date. Green-manuring was suggested by Xenophon about four centuries before the Christian Era (Ch. 1).

In the United States, green-manuring was first practiced by a few planters in Virginia and Maryland during the latter part of the eighteenth century. Now the practice is confined principally to the Atlantic Coastal Plain and the southeastern States. It is restricted mainly to orchards, although the value of green manure and its use in gradually becoming more generally recognized and adopted, particularly in districts where supplies of stable manures are limited and the use of commercial fertilizers is increasing.

Crops for green-manuring. Crops suitable for green-manuring may be classed as legumes and nonlegumes. Practically every region has adaptable crops that may be grown for this purpose. From Virginia to South Carolina, crimson or Italian clover, bur-clover, and vetch are commonly used for green manure, greatly increasing the yields of corn and cotton. Similar results have been obtained in other southern States with vetch, annual yellow melilot

Fig. 79. Organic matter increased the growth and yield of Indian corn in Alabama. Left—Average yield without green manure, 8.9 bushels to the acre. Right—Average yield with leguminous green manure, 33.8 bushels.

(*Melilotus indica*), cowpeas, Austrian winter peas, kudzu-beans (*Pueraria thunbergiana*), crotalaria, and other legumes (Figs. 79 and 80).

In general farming, great progress has been made in the use of green manures in the Cotton Belt, and likewise in the Corn Belt. The value of sweetclovers (*Melilotus*) for green-manuring is becoming recognized in growing Indian corn and sugar beets, and in improving poor soils.

In the western part of the United States, the crops used for green manure in truck growing are usually the same as those used for the same purpose in orchards.

In irrigated citrous orchards of Arizona, alfalfa, cowpeas,

sweetclover, and tepary beans are common summer green-manuring crops; and field peas, common vetch, and sourclover (*Melilotus indica*) are grown during the winter season. In the Salt River Valley of this same State, where the summer heat is intense and the winter climate is mild, the keeping of a permanent alfalfa cover in irrigated citrous groves is a common practice.

In southern California, sourclover and common vetch are com-

Fig. 80. Cotton, following leguminous green-manure crops, produced a yield of 1,626 pounds of seed cotton per acre, as compared with 426 pounds without legumes.

monly grown in citrous orchards. In this same State, the use of green manures and other organic materials have been found necessary to correct or obviate certain harmful effects attending the continual use of certain nitrogenous fertilizer salts (Ch. 16). In deciduous orchards of California, bur-clover, grasses, and weeds commonly function as cover crops during winter months and as sources of green manure in the spring. In apple orchards of Washington, Oregon, and the Rocky Mountain States, alfalfa is commonly used as a permanent cover crop and source of organic matter.

Legumes v. nonlegumes for green manure. The superior value of legumes for increasing the fruitfulness of the ground was known to the ancient Carthaginians and Romans. About 2,000 years

passed, after the first recorded reference to green-manuring with legumes, before the principal reason for this difference was discovered (Ch. 5). Another advantage offered by legumes concerns carbon-nitrogen relations. When soils contain considerable nitrogen, nonleguminous crops may be used for green-manuring without appreciable harm, so far as available nitrogen is concerned. But since comparatively cheap commercial sources of nitrogen have become available, nitrogen fertilizers may probably be used advantageously and economically in conjunction with carbon-rich or cellulose-rich green manures and other organic materials. The New Jersey potato growers use small grains extensively, particularly rye, for green manure, supplementing it with commercial nitrogen.

Microbiological aspects of green-manuring. The younger the plants are, when used as green manure, the more rapid are the processes of decomposition. Materials rich in nitrogen decompose faster than those poor in this element. Inasmuch as mature plants consist of from 60 to 65 percent of hemicelluloses, and celluloses and younger plants consist of about 40 percent of these substances, decomposition of mature tissues involves the assimilation of more nitrogen by the micro-organisms concerned than decomposition of younger tissue. These are important facts to consider in green-manuring, for there is involved the question of how much time to allow between the date of turning under the crop and planting, in order to obtain the best results.

In measuring the rate of decay of green manure, Potter and Snyder (1917) found that the addition of lime had a decidedly favorable effect upon decomposition. Concerning the quantity of green manure that may be turned under, Briscoe and Harned (1929), working with alfalfa material under southern conditions, have concluded that there is no danger in turning under as large green-manure crops as may be grown, if adequate water and basic elements (calcium and magnesium) are available.

According to Waksman (1929), the water-soluble organic constituents of green manures are the first to undergo decomposition. Then the micro-organisms attack the insoluble protein, hemicelluloses, and celluloses. As decomposition progresses, the rate becomes slower, owing to the resistance of the remaining substances like lignins.

Kind of plant material, soil microflora, moisture, aëration, soil reaction, and temperature are important factors that affect decomposition of manures in soils.

Green-manuring and soil nitrogen. Nitrogen that is liberated from green manures in decomposition is lost from soils if it is not assimilated by crop plants or micro-organisms, or both. Losses always occur. Lyon and Wilson (1928) have found that green manures differ in their effects regarding soil nitrogen. After 12 years (10 of continual cover-crop and annual green-manure treatment, with no harvested crops) it was found that buckwheat green manure caused a total loss of 412 pounds of soil nitrogen per acre; oats, 382 pounds; Canada field peas, 380 pounds; winter rye, 217 pounds; and winter vetch, 42 pounds. During the same period plots were kept continuously in grass, consisting of a mixture of Kentucky bluegrass (*Poa pratensis*), timothy (*Phleum pratense*), and redtop (*Agrostis alba*), which was cut once or twice each year and left on the ground. The soil under the grass gained 415 pounds of nitrogen per acre during the period of the experiment. White and co-workers (1945) obtained similar results.

These results suggest two ways to mitigate the loss of soil nitrogen: (1) by allowing land to lie undisturbed in grass for a period of years; and (2) by growing those cover crops (for green-manuring) that are most active, like vetch, in fixing soil nitrogen in plant tissue.

Cover crops that are used for green-manuring cannot prevent entirely the loss of soil nitrogen. Their value, so far as nitrogen and organic matter are concerned, consists in mitigating the loss, in making possible the utilization of the conserved nitrogen, and in supplying plant residues to counterbalance the gradual diminution of soil organic matter resulting from cultivation.

It does not matter what the carbon-nitrogen ratio of green manures may be—16 or 20 to 1 in legume materials to about 36 to 1 in green rye—the ratio will narrow or drop to about 10 or 12 to 1 before these materials have been incorporated into soils very long; this may be regarded as an equilibrium ratio. Further decomposition results in a more or less parallel liberation of carbon as carbon dioxide and of nitrogen as ammonia (nitrified to nitrates), with a tendency for the ratio to narrow somewhat. When soil organic matter reaches this rather stable condition, it is regarded

as having become ***humified.*** In such organic compounds the soil nitrogen may be regarded as fixed, and is not available for use by plants until decomposition and nitrification set in.

Some practical pointers on green-manuring. Owing to the fact that green-manure crops are turned under, no crop is apt to be widely or commonly used for such a purpose if it requires an entire season for its growth. Accordingly, it is desirable to choose

Fig. 81. Legumes for green manure may be grown in between rows of Indian corn, as is commonly done in certain districts in the southeastern States.

such crops for green-manuring as may be grown without losing the use of the land for an entire season. Rye, with or without legumes, may be sown in between rows of corn or late potatoes in the fall and plowed under the following spring for a second crop of corn or potatoes. Legumes may be grown in between corn rows for green manure, as is commonly done in certain districts in the southern States (Fig. 81).

Second growth of clover, rowen, and volunteer grain may be plowed under for green manure. Soybeans and other crops may be sown after small-grain harvest, and plowed under in the fall. Such plantings may serve as cover crops during fall and winter, and may be turned under for green manure in the spring.

It is commonly advisable to advance the time of plowing in spring when green-manure crops are to be turned under, in order

to allow development of favorable conditions with respect to soil moisture. The crop may have removed much soil water, and if much material is plowed under, it is important that proper contact be established between the furrow slices and between the seed bed and subsoil. Compactness of seed bed is highly desirable on sandy soils, particularly when considerable material has been incorporated.

When much material is to be turned under, it may prove to be advantageous to disk the land before plowing, in order to cut the material up and incorporate some of it into the soil. In plowing under vegetable growth, the use of a weedhook or drag chain may be helpful in getting the material turned down into the furrow and properly covered.

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REVIEW QUESTIONS

1. Distinguish between the different kinds or types of organic matter in soils.
2. Which function of soil organic matter is most important in soil fertility—the physical, the chemical, or the biological? Explain.
3. In regard to state of decomposition, what kind of organic matter is most important in soil fertility? Why? Chemically, what kind is usually the best?
4. What seems to be an important function of organic matter in orchards,

especially in connection with continual use of what particular kind of fertilizer?

5. Discuss the economic problem of "maintaining" soil organic matter. How does this problem differ in different climatic regions?
6. What are some of the problems attending the practice of green-manuring?
7. Discuss ways and means of economical green-manuring.
8. Give reasons why a nonleguminous green-manure crop may not give so good results as a leguminous one.

CHAPTER 19

SOIL MICRO-ORGANISMS AND SOIL FERTILITY

The fundamental relationship between soil micro-organisms and higher plants is principally one of nutrition. Higher plants supply sources of energy for the organisms which, in turn, supply important nutrients for crop plants while living on them or on organic matter. In the changes that take place in the rendering of the constituents of organic substances available for plants, it is impossible to distinguish between those caused by organisms, chemical reactions, and by proteolytic enzymes. However, the important changes may be tacitly attributed to micro-organisms; these changes may be regarded as microbiological. Many chemical processes are involved; but from the point of view of soil fertility, the microbiological processes may be designated as decomposition, mineralization, microbial assimilation and fixation of soil nitrogen, ammonification, nitrification, denitrification, fixation of atmospheric nitrogen, sulfofication, and parasitism.

DECOMPOSITION

Original organic matter, such as plant residues and other complex organic materials, cannot be used by crop plants; but through the action of micro-organisms, principally, they become valuable sources of nutrients. Here attention is called to the fact that in all mixtures of plant and animal tissues are found complex proteolytic enzymes which have the power not only to break down proteins, but also to cause union of different chemical substances.

Evolution of carbon dioxide. The simplest reactions in decomposition result in the evolution of carbon dioxide. Several investigators have used these reactions as an index of biological activity in soils. According to Russell (Eng., 1927) the quantity of carbon dioxide evolved varies widely, from 4 to 50 grams per square meter per day during summer. This corresponds to an absorption of from 2 to 26 liters of oxygen (Fig. 70). The carbon dioxide evolved from a cropped soil affects both the soil and the plants.

As carbonic acid, it dissolves certain soil minerals, and it is thought by some investigators to effect a condition of ripeness (leavening effect) after spring plowing and cultivation.

Several investigators have demonstrated that, through soil respiration, an enrichment of carbon dioxide takes place in the ground layer of the atmosphere. Stoklasa (Czech., 1926) has found that the quantity of carbon dioxide exhaled from soils may be used as a measure of the fruitfulness of soils, much more being given off from fertile than from unfruitful soils. Evolved carbon dioxide is partly exhaled from soils by diffusion and is partly absorbed by soil water in which the carbon is redeposited as carbonates.

Plants are not wholly dependent on the carbon dioxide of the free atmosphere for their carbon. Their leaves also assimilate that which escapes from soils. Thus the carbon dioxide that results from the activity of soil micro-organisms is an important factor affecting the nourishment of crop plants.

Humus formation. Colloidal humic substances, which are important soil constituents, may be counted among the most important products of decomposition of organic matter, resulting largely from the action of fungi, aërobic bacteria, actinomycetes, and also under water-logged conditions, by anaërobic bacteria acting principally on cellulose and lignin substances. According to Waksman (1931), this gives rise to nitrogen-poor humic compounds. On the other hand, microbial substances give rise to nitrogen-rich humus compounds.

Organisms and fertilizers. Were it not for soil micro-organisms, many materials added to soils would have no fertilizing value. In the use of stable manures, green manures, and organic fertilizer materials, soil organisms function in a most important way in rendering available the elements of plant food that are locked up in the complex organic materials.

Decomposition of toxins. Another important function of soil micro-organisms consists in decomposing certain intermediate products which, if allowed to persist in soils, would prove to be injurious to plants. Among these products are included certain phenolic compounds like dihydroxystearic acid which form in the decomposition of proteins, and which have been isolated from soils by Schreiner and Shorey (1908). Other toxic intermediate products are formed during decomposition of plant remains. A consider-

able number of soil bacteria are able to decompose such compounds as phenols, cresol, and naphthalene.

MINERALIZATION OF ORGANIC MATTER

Acting on nitrogenous or protein substances, soil micro-organisms, including bacteria and fungi, effect liberation of carbon, nitrogen, phosphorus, sulphur, and other elements which in the presence of active basic elements, particularly calcium, are converted into soluble mineral compounds, forming carbonates, nitrates, phosphates, sulphates, etc. This general process is known as *mineralization* of organic matter, and it is a most important function of micro-organisms.

MICROBIAL ASSIMILATION AND FIXATION OF SOIL NITROGEN

Attention has already been drawn to the fact that in decomposition of the simpler carbohydrates, celluloses, and pentosans, fungi and bacteria require nitrogen and mineral elements for the building of their protoplasm and tissue, and to aid in decomposition. Adding materials of wide carbon-nitrogen ratio like celluloses and the simpler carbohydrates to a soil may result in such rapid multiplication of organisms and increased assimilation of nitrogen as to cause injury to the crop, owing to depletion of available nitrogen. Between micro-organisms and crop plants, the former always lay first claim to available soil nitrogen. Furthermore, they have a decided advantage over higher plants in being able to assimilate their nitrogen before it is converted into the nitrate form. The problem of depression of available soil nitrogen resulting from microbiological activity may be solved by supplementing the use of carbon-rich materials with quickly available fertilizer nitrogen.

It has been found that when plant residues contain less than about 1.7 percent nitrogen, additional available nitrogen will be required to decompose the organic matter in a reasonable length of time. This accounts for the utilization by fungi and bacteria of nitrogen, which is ordinarily rendered available from the soil supply of organic matter when cellulose and easily decomposable carbohydrates are added to soils. It is only when the added excess of available energy, or carbon, over nitrogen has been used up that nitrogen is liberated in a soil as ammonia and converted into nitrates for use by higher plants. According to Heck (1929), fungi

may be largely responsible for the rapid depression of mineral nitrogen when the energy or carbon supply of a soil is increased.

Microbial fixation of soil nitrogen. Soil nitrogen assimilated by fungi and bacteria becomes fixed in the complex organic substances of which these organisms are composed. Mycelial tissue of fungi probably constitutes a large part of soil micro-organic materials. This microbial nitrogen is not lost from soils nor is it permanently lost to crop plants. Through decomposition of the organisms or through auto-digestion after their death (autolysis), much of the nitrogen of most micro-organic substances, according to Barthel and Bengtsson (Swed., 1928) and Heck (1929), is liberated and mineralized. Some of it may not be liberated or may again be combined into microbial substances.

From the point of view of soil fertility, it may be said that the quantity of soil nitrogen that becomes available to crops represents a balance between nitrogen that is liberated through decomposition of nitrogenous organic matter and that which is assimilated by the micro-organisms that decompose nitrogenous and non-nitrogenous soil materials.

AMMONIFICATION

Ammonification has been defined as the formation of ammonia as a by-product in decomposition of nitrogenous compounds. Ordinarily, the ammonia formed is immediately mineralized to nitrates which constitute the principal sources of available soil nitrogen. Ammonia may be formed by a large number of soil micro-organisms, including fungi, aërobic and anaërobic bacteria, and actinomycetes.

Probably not all soil ammonia is formed by micro-organisms, as some may be evolved even in the presence of antiseptics which are supposed to kill organisms. Some investigators have obtained evidence that amino acids may form in decomposition of protein, which on hydrolyzing or oxydizing give rise to ammonia.

Ammonifiers may compete with crops. The fact that ammonia formation in soils is caused by living agents was established by Müntz and Condon (Fr.) in 1893; but the relation between energy and nitrogen in connection with these organisms was not discovered until 1916, when Doryland found that the ammonifiers require energy primarily. They prefer carbohydrates as sources of energy, but act upon protein to obtain their nitrogen. In the absence of available carbohydrates, they decompose protein, with liberation

of ammonia as waste product. But in the presence of available or suitable carbohydrates (preferred sources of energy), multiplication of these bacteria and fungi is stimulated, less protein is decomposed, and less ammonia is produced. When the production of ammonia decreases to zero, the ammonifying organisms may compete with growing crops for available nitrogen.

Owing to the activity of soil micro-organisms, it is important to know the character of the organic matter that is added to soils in the form of crop residues, farm manures, and green manures.

Ammonia toxicity. Under certain conditions, ammonia may form and accumulate in sufficient quantities to injure seedlings of crop plants. Willis and Rankin (1930) have found that easily ammonified fertilizer materials like cottonseed meal and diammonium phosphate, $(NH_4)_2HPO_4$, may give rise to sufficient free ammonia to cause severe injury to cotton seedlings (roots) on light sandy soils that have low absorptive power. The remedy suggested is to supply gypsum or any other calcium salt as an ingredient in fertilizer mixtures that contain easily ammonified materials, in order to neutralize the free ammonia. The injury may also be controlled by timing fertilizer application and planting so as to allow the ammonia to dissipate by diffusion or volatilization before the seedling stage is reached.

NITRIFICATION

Nitrification may be defined as a process of oxidation by which ammonia is converted first into nitrites and then into nitrates through the action of bacteria. According to Russell,[1] the ammonia that is formed in soils is first changed to ammonium carbonate which is rapidly converted into nitrite, and then the nitrite is quickly oxidized to nitrate. The raw material in nitrification is ammonia.

Oxidation of ammonia to nitrite is brought about by specific autotrophic bacteria which are classed as *Nitrosomonas* and *Nitrosococcus*. These convert only ammonia into nitrites. The other bacteria concerned are classed as *Nitrobacter*, and they are equally as specific as the former. They oxidize only nitrites into nitrates.

Both groups of nitrifying organisms obtain their carbon by synthesis from carbon dioxide, as they are unable to utilize organic compounds as sources of carbon. The energy used by the nitrite-

[1] RUSSELL, E. J. Soil Conditions and Plant Growth. 6th edition, p. 327. 1932.

forming bacteria for assimilating carbon dioxide is derived in oxidation of ammonia to nitrites, and they may derive their nitrogen from either ammonia or ammonium compounds. The nitrobacters obtain their energy for assimilating carbon dioxide by oxidizing nitrites, and they derive their nitrogen from nitrites.

It is not known whether there are other distinct species of *Nitrosomonas* that are able to oxidize ammonia to nitrites. And of the genus *Nitrobacter*, one kind, commonly called "nitrifiers," are the only organisms that are definitely known to produce soil nitrates.

Ordinarily, in arable soils, there is no accumulation of ammonia nor of nitrites, as these are quickly oxidized. Fraps (1930) has found that in soil materials having low nitrifying powers large quantities of nitrites may form, but that under field conditions only very small quantities may accumulate.

Importance of nitrification. Nitrates that are produced in soils constitute the principal sources of available nitrogen for practically all agricultural plants, paddy rice being an exception. Nitrification, therefore, is a most important biological process in soils. It represents a vital relationship between complex, insoluble, nitrogenous compounds, on the one hand, and growing plants, on the other. It may be said that the existence of human beings, animals, and higher plants depends largely on the activity of the specific nitrifying micro-organisms (*Nitrosomonas*, *Nitrosococcus*, and *Nitrobacter*) because of the contribution of available nitrogen that they make to the plants.

Nitrification takes place in practically all soils, though in varying degrees, as determined by soil conditions with respect to moisture, aëration, reaction, temperature, physical condition, and content of organic matter (Fig. 82). The bacteria concerned cannot tolerate free ammonia. When an arable soil is saturated with water, as when a field becomes flooded, nitrification ceases for lack of oxygen. Under such conditions, crops commonly suffer for want of available nitrogen, as may be indicated by yellowing of the leaves. When the excess water drains out and air enters, the nitrifying organisms again become active.

Generally, in soils of humid regions, nitrification depends on ammonification. Little ammonia is lost in the process. Under hot arid and semiarid conditions, ammonia may form in excess of the capacity of the nitrobacters to use it, which excess may injure plants.

Rate of nitrification. The rate of nitrification in soils varies greatly. In well-aërated soils that are rich in organic matter, the rate may be great enough to result in an excess of nitrates over the amount required by growing crops. In soils low in organic matter, crops may absorb the nitrates so quickly that there is no accumulation during vegetable growth.

Yields of 20 tons of cabbages and of 165 bushels of Indian corn per acre on highly productive soils indicate nitrate production

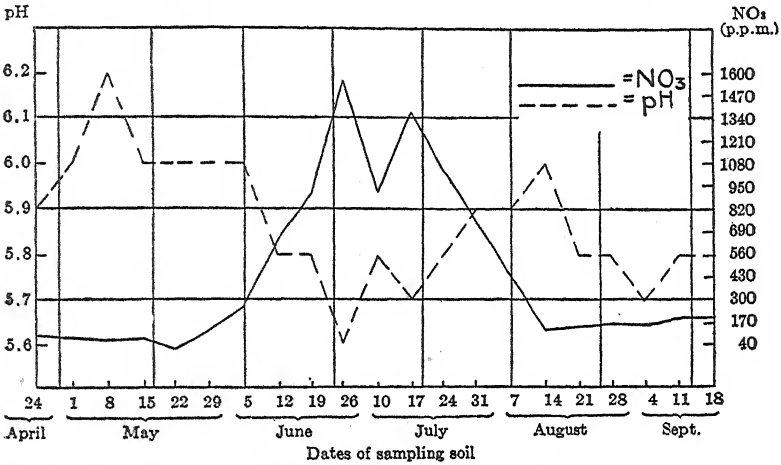

Fig. 82. Seasonal fluctuation in nitrification, and relation between pH values and nitrification in the surface 4-inch layer of a muck soil in New York State.

sufficient to supply at least 140 and 240 pounds of nitrogen per acre, respectively. Inasmuch as available nitrogen is the most common limiting factor in crop production, the nitrogen requirement of crops may serve to indicate the rate at which nitrification ordinarily takes place in soils. A 30-bushel wheat crop requires about 52 pounds of nitrogen per acre, a quantity equivalent to about 305 pounds of pure calcium nitrate or about 316 pounds of pure sodium nitrate.

Rate of nitrification varies with the seasons of the year. Whiting and Schoonover (1920), in Illinois, found late spring and early summer to be the period of most active production and accumulation of soil nitrates, for the reason that during this period optimum temperature and moisture conditions are approached. A second active period commonly occurs in the autumn when there is a

second approach to optimum conditions for nitrate production. During midsummer, except when the weather is cool and moisture supply adequate, little nitrate production takes place; and during adverse conditions of winter, none. Starkey (1931) found that when other conditions were equal, nitrification was most active in soils with maximum root development.

Absorption of nitrates. In general, the period of greatest absorption of nitrates by crop plants corresponds with the period of greatest production, although the period of greatest utilization varies with different species. For wheat and oats, for example, the period of greatest assimilation of nitrates is earlier in the growing season than for maize. There may also be a close relationship between period of greatest utilization of nitrates and soil treatment, as may be illustrated by side-dressing 18-inch-high maize with quickly available nitrogen.

Crop plants affect nitrate production. Growth of higher plants may affect the formation of soil nitrates to a marked degree. In their study of nitrates under different plants growing on the same kind of soil, Lyon and Bizzell (1913) found different quantities of nitrate under timothy, maize, potatoes, oats, millet, and soybeans. Characteristic differences in quantity were found at different stages of growth. They concluded that crops may exert marked influences on the process of nitrate production. Furthermore, nitrate formation under a given crop may be affected by the previous crop.

These investigators found that timothy maintained a lower nitrate content in the soil than did any of the other crops, and that mixed grasses (timothy, redtop, and bluegrass) gave much less total nitrogen in the crop and drainage water than was contained in the drainage water from uncropped soil. These facts indicate a strongly repressive influence of these grass plants on nitrate formation, and point to a possible cause of the injurious effects of permanent grass sod in orchards, especially on soils in which the supplies of available nitrogen are deficient.

Nitrate and carbohydrate relations. The bacteria that effect nitrification in soils supply nitrogen to most of the other soil micro-organisms. Nitrates that micro-organisms do not need are either utilized by growing plants or are leached out, and they disappear in drainage waters. The nitrogen that micro-organisms assimilate is not permanently lost. It is released on their death and decom-

position, and through nitrification ultimately becomes available to crops.

Events leading to knowledge of soil nitrifiers. Formation of niter in niter beds or from organic matter was known to the ancients, but the process remained unknown for many centuries. Formation of nitrates in soils was known during the seventeenth and eighteenth centuries, but no relation between this fact and plant growth was even suspected. Liebig contended that plants utilized nitrogen as ammonia. But Boussingault (Fr.) recognized a relationship between nitrate formation and plant nutrition about 1855. Müller (Ger., 1873) was the first one to suggest that the nitrate-forming process in soils was biological. Following the work of Schloesing and Müntz (Fr., 1877) on nitrification of sewage, Warington (Eng., 1878) found that nitrification in soils involved two different organisms and two different processes. Winogradsky not only proved that soil nitrification is bacterial, by isolating representatives of each group, but also established a scientific explanation for it (1890-1892).

Dhar and co-workers (India, 1933-1946) believe that nitrogen transformations, also nitrogen fixation, can take place in soils without bacteria, chemically and photochemically with organic substances.

DENITRIFICATION

Denitrification is the reduction of nitrates and nitrites, by bacterial action, to oxides of nitrogen (N_2O, NO) and elemental nitrogen (N_2), in which forms the nitrogen escapes into the atmosphere. This destructive process takes place in the absence of free oxygen but in the presence of an abundance of easily oxidizable organic matter which serves as a source of energy for the organisms concerned.

It is probable that free nitrogen may also be liberated in decomposition of soil organic matter, consequent to rapid oxidation of the ammonia produced.

Economic importance of denitrification. Conditions in well-cultivated soils do not favor denitrification even though considerable organic matter and nitrates may be present. Voorhees (1899-1904) has shown that in ordinary cultivated soils denitrification is of questionable economic importance.

When a planted field becomes flooded or a soil becomes saturated with water and remains so for a considerable length of time, the

crop may suffer for want of available nitrogen due to cessation of nitrification, denitrification, or nitrate assimilation by soil micro-organisms, as in flooded places in fields of young grain.

In their study of soils that produce paddy rice, Metzger and Janssen (1928) and Bartholomew (1929) found that application of nitrate fertilizer resulted in loss of nitrogen through denitrification; this fact accounted for chlorosis or injury to the crop.

Liberal use of lime on acid peat soils has been found to cause loss of nitrogen through reduction of nitrates to nitrites and gaseous nitrogen.

FIXATION OF ATMOSPHERIC NITROGEN BY SYMBIOTIC BACTERIA

Bacteria that fix atmospheric nitrogen symbiotically in nodules on roots of leguminous plants have been classed in the genus

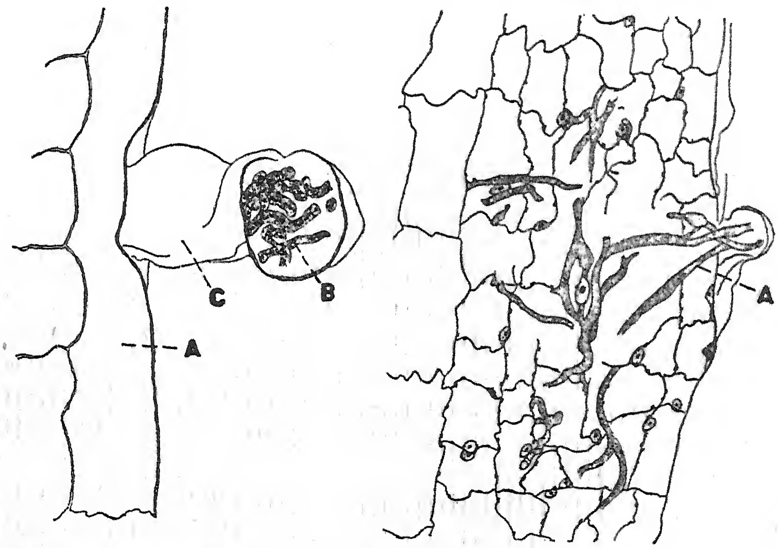

Fig. 83. Infection of a root by nodule-forming bacteria. Left—Cross-section of a part of an infected root hair (C) of the main root (A). B, Multiple-infection thread within a root hair. Right—Penetration of infection threads (A) into a root. (After McCoy.)

Rhizobium. Fred, Baldwin, and McCoy (1932) have grouped rhizobia into 15 species, based on similarity, particularly as manifested in "cross-inoculation" of legumes.

Legume bacteria, which are widely distributed in nature, pass a part of their cycle of life in soils outside of nodules, where they can

exist for years without the presence of host plants. In this independent state they exist in cell forms which seem to constitute definite stages in their life cycles. At certain stages in their life cycles small motile, rounded cells are formed which are able to move rapidly about in the soil mass. Probably in this stage they reach the roots of their respective host plants.

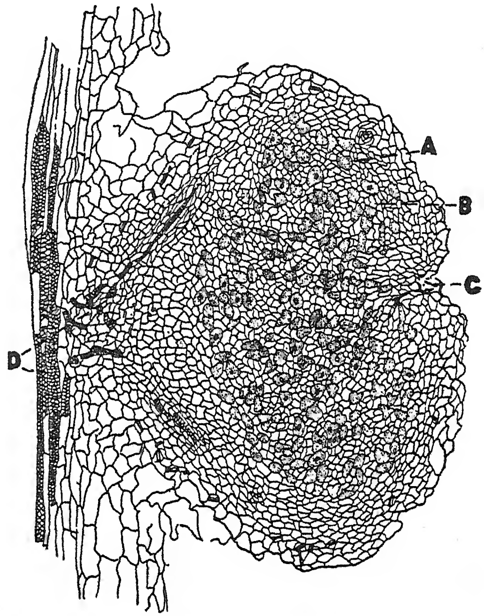

Fig. 84. A well-grown nodule cut in nearly median section: A, bacterial cells; B, intermediate starch-bearing cells; C, remains of primary infection thread; D, vascular bundles in the nodule and central cylinder of a root.

How nodule bacteria work. When nodule-forming bacteria come in contact with roots of the host legume, they enter the single-celled root hairs. Within the root, they multiply rapidly, causing the formation of nodules (Figs. 83 and 84). The number of nodules that may develop on the roots of a single plant may vary from a few to several thousand. Each nodule contains millions of bacteria. The host plant, in addition to removing by-products, also supplies the bacteria with carbohydrates which are produced in the leaves by photosynthesis. It is assumed that in return the nodule bacteria supply the host plants with nitrogen. It is true, nevertheless, that the plants do obtain nitrogen from this bacterial source. About the time when seeds begin to mature, the nodules cease growing and finally become empty, during which time the bacteria move out into the soil mass.

Until recently it was believed that rhizobia, or nodule-forming bacteria, cannot fix atmospheric nitrogen in soils independently of host plants, or legumes. But Virtanen (Fin., 1944) has found substantial evidence that these nitrogen-fixing bacteria survive in soils without the assistance of higher plants and that they do not transfer

nitrogen to host plants. On the contrary, these bacteria emit into the soil generous quantities of aspartic acid, which they synthesize within their own cells. Aspartic acid is an essential component of proteins, and its various forms are not amino acids. Whether there are nodules or no nodules, the aspartic acid is the source of nitrogen from which plants may obtain nitrogen through the aid of rhizobia.

Thus an explanation of the beneficial effects of legumes on soils, recognized many centuries ago by the ancient Carthaginians and Romans (Ch. 1), has been established.

Events that led to this knowledge. Nodules on roots of legumes were known for a long time, but they were regarded as root galls. Davy (Eng., 1814) stated that the nitrogen of protein-like substances of peas and beans seemed to have its origin in the air. Boussingault (Fr., 1838) was the first scientist to initiate experiments on nitrogen nutrition of leguminous and nonleguminous plants. He found that clover and peas increased the nitrogen content of unmanured soil material, but he could not explain his results. Twenty years later he concluded that the increased nitrogen came partly from ammonia supplied by water he had used and partly from the air. In 1860, he concluded that crop plants could not assimilate nitrogen of the air without the aid of bacteria.

Observing that certain bacteria caused the formation of nodules, Lachmann (Ger., 1858) suggested that nodules were organs of nitrogen-fixation. Hellriegel (Ger., 1863) found that clover could grow in sand cultures containing all essential nutrients but nitrogen.

Up to this time, most investigators thought that the causal organism was a fungus. But later, in 1866, Woronin (Fr.) found that nodules contained bacteria-like organisms, but he regarded the tubercles as a diseased condition. Frank (Ger., 1879) demonstrated that nodule formation (a form of parasitism) could be prevented by soil sterilization. He believed that legume bacteria belonged to the same species that he named *Schinzia leguminosarum*. Atwater came very near the truth when, in 1884, he demonstrated that root nodules were the result of bacterial infection, and pointed out that the bacteria fixed atmospheric nitrogen.

The work of Berthelot (Fr., 1885), who attributed a gain of nitrogen in unsterilized soil materials in large closed flasks to micro-organisms, suggested to Hellriegel and Wilfarth the clew

to the solution of the legume problem, which led to their discovery of symbiotic fixation of atmospheric nitrogen by nodule bacteria in 1886 (Ch. 5). It remained for Beijerinck (Ger.) to isolate the organism, which he did in 1888.

Quantity of nitrogen fixed in nodules. The quantity of nitrogen that may be fixed by nodule bacteria varies according to soils and crops. In general, there may be a gain of from 30 to 200 pounds of nitrogen (N) per acre of legume.

C. G. Hopkins (1904) investigated the fixation of nitrogen by legumes, and obtained the following information: a 4-ton crop of alfalfa fixed 132 pounds of nitrogen per acre; a 4-ton clover crop added 106 pounds; a 25-bushel soybean crop, with 2¼ tons of straw, added 106 pounds; and a 3-ton crop of cowpeas fixed 86 pounds of nitrogen per acre. He found that legumes growing on ordinary productive soils obtained about two thirds of their total nitrogen from the atmosphere, which in clover and alfalfa amounts to about the proportion contained in the tops (hay). Accordingly, the quantity contained in the roots and stubble about equals the quantity obtained from the soil reserves.

Whiting (1915) found 74 percent of the total nitrogen of soybeans and cowpeas in the tops. The proportion may be less or greater, depending on degree of nodulation. Wheeler (1912) obtained results that indicated an annual gain of as much as 400 pounds of nitrogen per acre. Shutt (Can., 1912) found a net gain of 50 pounds of nitrogen per acre by clover on light sandy soil. Lipman and Blair (1916) obtained an average annual gain of 54 pounds of nitrogen per acre in cylinder experiments, from growing legumes in rotation with maize, potatoes, oats, and rye. On a sandy soil, with inoculated soybeans, Fred (1921) obtained a gain of about 65 pounds of nitrogen per acre in a yield of about 2,400 pounds.

In general farming, the quantity of nitrogen added to a soil by legume bacteria depends on what disposition is made of the legume crop. If clover or alfalfa, for example, is plowed under for green manure, the quantity of nitrogen added to the soil would be the total quantity of atmospheric nitrogen fixed by the crop. If the crop is cut and removed from the field, there may be but little or no gain of soil nitrogen. If the crop is cut for hay, and the

manure produced in feeding the hay is applied to the field that grew the legume, the soil would be enriched by about half of the nitrogen fixed from the air by the crop. If the fertilizing con-

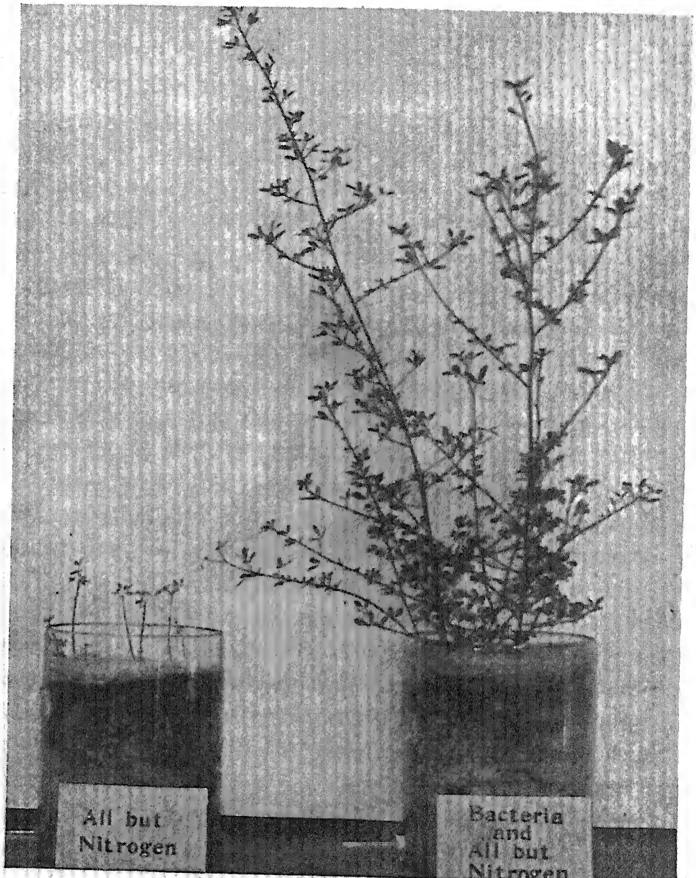

Fig. 85. Uninoculated and inoculated sweetclover growing in nitrogen-deficient soil mediums.

stituents of manure are conserved, it may be possible to add about 60 percent of the fixed nitrogen to the soil.

More nitrogen is fixed in soils poor in nitrogen but supplied with available mineral elements than in rich soils. Furthermore, best results are obtained when soils are well populated with the particular kind of nodule-forming bacteria concerned (Fig. 85).

Inoculation of legumes. The discovery and isolation of nitrogen-fixing bacteria suggested the idea of inoculating legumes with nodule bacteria to increase crop yields. In fact, long before nitrogen-fixation by bacteria became known, farmers of the Netherlands obtained benefits from scattering small quantities of soil material, taken from fields in which legumes had been successfully grown, over newly cultivated lands, especially sand and peat. But the first scientific experiment was made at Bremen, Germany, in 1887. In this test, which proved to be successful on land supplied with lime, a good stand of clover was obtained on some reclaimed swamp land to which had been added soil material taken from a clover field.

Most of the results of the early use of artificial inoculation materials proved to be unsatisfactory, because of imperfect knowledge. Several investigators in Europe also tried inoculating nonlegumes, but failed. Bacterial cultures for legume-inoculation purposes have appeared on the market, and, through improvement by scientific investigations, have been increased in value for use by farmers. Improved cultures of bacteria for inoculation of legumes are now distributed by agricultural experiment stations, other agricultural institutions, and commercial concerns. Inoculation of nonlegumes and of soils with various other bacteria has been tried, but without beneficial results.

Legumes must either find nodule-forming bacteria in soils or be supplied with them in order that full benefits from their growth may be obtained (Fig. 86). Inoculation is advisable when legumes are grown for the first time in a locality, to assure success on limed acid soils, and for introducing more vigorous strains.

Cross inoculation. Some of the rhizobia can invade the roots of only one kind of legume, those of soybeans, for example. Others can form nodules upon a number of different legumes. Red-clover bacteria, for example, may be used to inoculate the common clovers. The use of the bacteria of one legume to inoculate another is commonly called "cross inoculation."

On the basis of cross inoculation, Fred, Baldwin, and McCoy (1932) have grouped the rhizobia into 15 species, as follows:

1. Alfalfa group (*Rhizobium meliloti*), including bacteria that may cause the formation of root nodules upon plants of the genera *Melilotus* (white sweetclover, yellow sweetclover, and sourclover or *M. indica*),

Medicago (alfalfa, black medic, buttonclover, spotted medic, horned medic, and bur-clovers), and *Trigonella* (fenugreek).

2. Clover group (*Rh. trifolii*), including bacteria that may form root nodules upon clovers (red, white Dutch, alsike, crimson, mammoth, hop, rabbitfoot, Carolina, Hungarian, and buffalo).

3. Pea group (*Rh. leguminosarum*), including bacteria that cause the formation of nodules upon plants of the genera *Lathyrus* (sweet, ever-

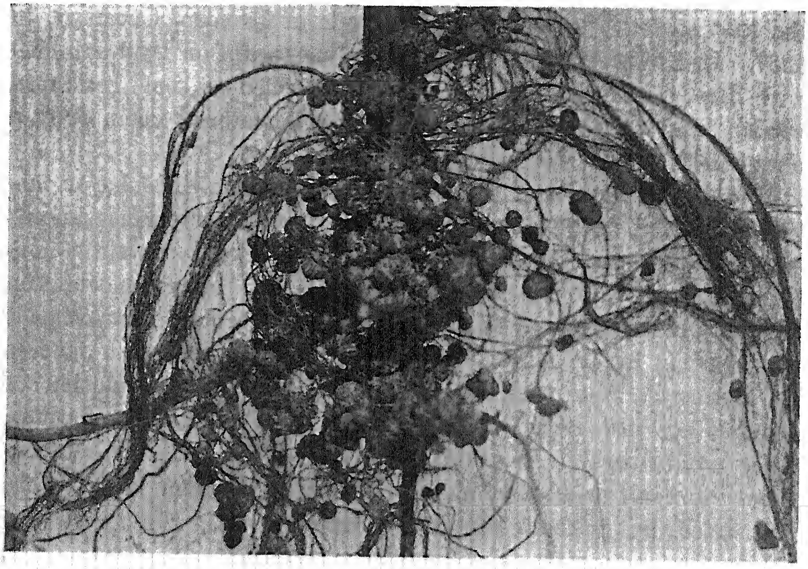

Fig. 86. Well-inoculated root of a soybean plant.

lasting, flat, and tangier peas), *Pisum* (garden and field peas), *Vicia* (vetches and horsebean or broadbean), and *Lens* (common lentil).

4. Bean group (*Rh. phaseoli*), bacteria that form nodules upon plants of the genus *Phaseolus,* such as kidney or navy (haricot) beans and scarlet runner.

5. Lupine group (*Rh. lupini*), including bacteria that cause the development of nodules upon plants of the genus *Lupinus* (yellow, blue-flowered, many-leaved, and white lupines) and on serradella.

6. Soybean group (*Rh. japonicum*), bacteria that develop nodules on soybeans.

7. Cowpea group, including bacteria that form nodules on roots of cowpeas (*Vigna sinensis*), partridge-peas, peanuts, lespedeza or Japan clover, velvetbeans, wild-indico, tickclover, and beggarweeds (*Desmodium* spp.), acacias, lima beans, tepary beans, kudzu-beans, and Florida velvetbeans.

8 to 15. Eight small and less important groups.

The alfalfa bacteria have become widely distributed throughout the United States and other countries by the spread of sweetclovers along railroad right of ways and roadsides, and by the growing of alfalfa and sweetclovers by farmers. In regions of limited rainfall, where soil acidity has not developed, soils are usually well stocked with these organisms. The wide distribution of the common clovers indicates the common occurrence of the red-clover bacteria.

Lasting effects of inoculation. Under favorable conditions, legume bacteria can exist for years in soils in the absence of host plants; therefore, when a legume is successfully inoculated in a field it is not necessary to repeat the inoculation, unless soil conditions become unfavorable, or a legume requiring different bacteria is to be grown, or a more vigorous strain is to be introduced.

It has been found that within a given variety of rhizobia the nitrogen-fixing power or vigor of the bacteria may vary considerably. So-called "vigorous strains" of bacteria lose their activity when they are grown in soils in the absence of host plants, and perhaps under adverse soil conditions.

Inoculation with soil materials. If a soil grows a certain legume successfully, and if many nodules occur on the roots, soil material from such a field may be used for introducing the bacteria into other fields for the same crop or for legumes that harbor the same kind of rhizobium.

Soil material for transfer should be friable in order to facilitate distribution. The top crust to a depth of about 1 inch should be scraped away, and then the soil material should be taken to a depth of about 5 or 6 inches. From 200 to 500 pounds per acre, evenly distributed, will give adequate inoculation. This may be broadcast by hand or distributed through the fertilizer attachment of the drill when seed is sown. Although legume organisms can withstand the rays of the sun to a considerable degree, excessive exposure is to be avoided. Accordingly, it is advisable to harrow the added soil material into the ground as soon as possible after application.

Soil material for inoculation purposes may be mixed with the seed and sown with it, mixing equal parts by weight of soil material and seed.

The glue method, devised by the Illinois Agricultural Experiment Station (1911), is commonly used. This consists of first moisten-

ing the seed with a dilute solution of ordinary cabinet-maker's glue (3 oz. to 1 gal. of water), using 1 pint of the cooled solution to 1 bushel of seed. The seeds are stirred to spread the glue solution evenly over them, and then fine or sifted inoculating soil material (preferably dry) is added at the rate of 1 quart to 1 bushel of seed, and thoroughly mixed with the seed. The mixture is then spread out and allowed to dry before bagging and seeding.

A modified form of this method is to mix a peck of soil material in a tub of water, in order to extract the organisms, and then pour the clearest water into another vessel and add some liquid glue. With this, wet the seed, and also sift on soil material; then dry the seed in shade.

Inoculation with pure cultures. Pure cultures of legume bacteria are prepared in liquid and agar forms. The liquid cultures are ready for use, but the others must be shaken with water to obtain a suspension of the organisms. Both the liquid and suspensions are usually applied to the seeds.

The principal requirements for successful inoculation are good soil tilth, good seed, and available calcium, magnesium, phosphorus, and potassium. These requirements must be given first consideration.

FIXATION OF ATMOSPHERIC NITROGEN BY NONSYMBIOTIC BACTERIA

The same year in which Lachmann (Ger., 1858) observed that certain bacteria caused the formation of nodules, Boussingault (Fr.) wrote: "Vegetable earth contains not only dead organic matter, but living organisms. The mycoderms have only an ephemeral existence and they leave their detritus in the soil which in turn may give rise to ammonia and nitric acid."

Boussingault was not aware of the fact that his statement contained the explanation of the gain of nitrogen in soils kept bare of vegetation.

Systematic inquiry into the problem of the recuperative power of soils with regard to nitrogen was begun by the noted French scientist, Berthelot, in 1885. Finding that unsterilized sandy and clayey soil materials had gained in nitrogen, he inferred that the increase was caused by micro-organisms. Although he did not succeed in isolating any causative organism, his work suggested to Hellriegel and Wilfarth the clew to the legume problem, and led to the discovery of *Clostridium pasteurianum* by Winogradsky

in 1893 and of *Azotobacter chroococcum* by Beijerinck in 1901. The latter bacteria are the most common of the free nitrogen-fixing organisms, and they occur more commonly in cultivated than in virgin soils. Many soils in regions of limited rainfall, as in the arid regions of the United States, have rich, active nitrogen-fixing microfloras, owing to their favorable composition.

Azotobacters are widely distributed in nature. They have been found in soils of favorable reaction and other favorable conditions in practically every locality where examinations have been made, including hot and cold regions, wet and dry localities, and places having fertile soils, barren sands, recently deposited volcanic materials, subsoils, drainage and sea waters, forests, and meadows.

How nonsymbiotic bacteria work. The free-living nitrogen-fixing bacteria derive their energy mainly from the simpler carbohydrates and alcohols, and their mineral nutrients from soil sources. They are dependent on other micro-organisms for breaking down cellulosic materials into available carbohydrates. The nitrogen that they fix is stored within their own bodies until they die or are consumed by protozoans. When they die, and on the death of the protozoans, the combined organic nitrogen becomes available for plants through the action of ammonifying and nitrifying micro-organisms.

These bacteria do not fix air nitrogen because of necessity, but because they are able to do so. If they can obtain the nitrogen they need with less expenditure of energy, no nitrogen will be fixed. It has been found that these bacteria will multiply very rapidly in the presence of much available nitrogen and comparatively little carbohydrates, as when heavy applications of rich, nitrogenous fertilizer materials are made. Under such conditions they may actually compete with crop plants for nitrogen, resulting in a temporary shortage or depression of nitrates.

Quantity of nitrogen fixed by free-living bacteria. The quantity of nitrogen fixed by nonsymbiotic nitrogen-fixing bacteria may vary from about 10 to 25 pounds per acre annually. Under favorable conditions the quantity fixed may amount to about one half the total quantity of nitrogen that is utilized by a crop. Thus the economic importance of these organisms is far greater than is commonly believed.

Not all soils have these bacteria, because of acidity (pH 6 and lower) and high alkalinity (pH 9 and higher). Azotobacters of

some species can fix nitrogen at reactions that range from pH 3 to 9. According to Martin (1940), calcium and/or sodium (3,000 or more p.p.m.) seem to limit them in strongly alkaline soils.

SULFOFICATION

The transformation of sulphur, mainly by bacteria, in organic and inorganic compounds to available sulphate forms has been called "sulfofication" by Brown and Kellogg (1914). In its transformation and in the types of organisms concerned, sulphur resembles nitrogen. Various heterotrophic bacteria, fungi, and actinomycetes are involved in the processes that result in the liberation of sulphur as hydrogen sulphide (H_2S) which, in turn, is oxidized by certain other bacteria to sulphur and then to sulphuric acid. The acid combines with soil basic elements and forms sulphates. Under anaërobic conditions, specific bacteria reduce sulphates to hydrogen sulphide (gas).

PARASITISM

By parasitism in soils is meant the action of parasitic micro-organisms on crop plants. Many of these parasites are distinctly detrimental to agricultural plants, including fungi, bacteria, and nematodes. Soils may harbor vast numbers of disease-forming fungi, some of which are most destructive parasites, including those that cause damping-off diseases of seedlings, certain cabbage diseases (yellows, particularly), mildews, potato "blight," certain rusts, wilt diseases, scab diseases, wart disease and dry rot of potatoes, and leaf diseases. "Soil sickness," as in greenhouses, may be a case of parasitism.

Among diseases caused by parasitic bacteria that may inhabit soils may be mentioned wilt diseases of tomatoes and potatoes and soft rots of a number of vegetables.

Nematodes of microscopic size and of parasitic type commonly infest soils, and cause injury to potatoes, tomatoes, clover, wheat, oats, tulips, onions, carrots, sugar beets, and in tropical regions to coffee, bananas, oranges, rice, and tobaccos. They may also be troublesome in soils of semiarid regions.

CONTROL OF SOIL MICRO-ORGANISMS

In relation to soil fertility, the ultimate aim of soil microbiologists is to gain full knowledge of soil micro-organisms in order to

control their beneficial activities or check the development of harmful activities through liming, soil aëration, addition of organic matter, application of fertilizers, control of certain parasites, partial sterilization of soils, cropping, control of moisture supply, and inoculation of soils with beneficial bacteria.

Liming in relation to control of soil organisms. Inasmuch as soil acidity is perhaps the most potent factor in reducing the activities of bacteria and excluding them from soils, liming may be regarded as the most important farm practice whereby soil fertility may be increased by affecting the soil population.

The presence of available calcium and magnesium in soils, as may be indicated by slight acidity or neutral reaction, greatly favors the activity of those organisms that effect decomposition and mineralization of soil organic matter, ammonification, nitrification, sulfofication, and fixation of atmospheric nitrogen.

In the following table are summarized, from various sources, the limit of acidity tolerance and the best or optimum soil reaction for important soil micro-organisms. For the *Rhizobium* groups, compare with those grouped earlier in this chapter.

RELATION OF SOIL REACTION TO ACTIVITY OF BENEFICIAL SOIL MICRO-ORGANISMS

Soil Micro-organisms (Indicated by Processes and Names of Groups of Organisms)	Limit of Acidity Tolerance	Range of the Best or Optimum Reaction
	pH	*pH*
Decomposition and mineralization of organic matter	1.2 *	6.5 to 8.5 †
Ammonification	1.2 *	6.5 to 8.5
Nitrification (*Nitrosomonas* and *Nitrobacter*)	3.2 to 4.6	6.5 to 7.5
Sulfofication	0.6 to 1.2	3.0 to 9.0
Rhizobium meliloti (alfalfa group)	4.9	7.0
Rhizobium leguminosarum (garden peas, field peas, vetches)	4.7 to 4.8	7.0
Rhizobium trifolii (red-clover group)	4.2 to 4.7	6.5 to 7.0
Rhizobium phaseoli (kidney beans)	4.3	6.5
Rhizobium japonicum (soybean)	4.2	4.8 to 6.5
Lupine bacteria	3.2	4.5 to 6.0
Austrian field peas	low pH	6.0 to 6.8
Serradella	—	6.0 to 6.8
Velvetbeans	3.3	6.0 to 6.8
Azotobacter	5.6 to 6.0	7.0 to 7.8
Clostridium pasteurianum	5.0 to 5.7	6.9 to 7.3

* *Aspergillis niger.*
† *Bacillus subtilis* (hay bacillus).
NOTE: In observing the relation of media reaction to symbiotic nitrogen-fixing bacteria, one should consider the fact that the host legumes concerned are affected markedly by mineral nutrition, particularly in regard to calcium.

According to Gerretsen (Holl., 1921), the limit of acid tolerance for nitrifying bacteria depends on their origin; those isolated from

acid soils are better adapted to acid conditions. It is known that nitrification can take place freely and continuously for long periods in strongly acid soils. Hall and co-workers (Eng., 1908) have explained this by the fact that under strongly acid conditions nitrates may form at points in a soil where the reaction is favorable, as around tiny particles of calcium carbonate. Vigorous nitrification is known to take place in certain acid forest soils.

The addition of lime to acid cultivated soils increases the formation of nitrates generally, aids nitrification and mineralization of green manures, and favors nitrification of acid-forming fertilizers like sulphate of ammonia.

Lime (calcium and magnesium) does not directly affect the nitrifying bacteria so much as it serves to neutralize acids that form as by-products, as in the nitrification of ammonium sulphate.

It is to be noted that, although most legume bacteria favor conditions when soil reaction is adjusted to about pH 6.5, some are able to withstand greater acidity than others, thus accounting, at least in part, for the fact that some legumes are especially well adapted for so-called "acid agriculture." The reaction that is best for most of the beneficial soil micro-organisms is about the same as that which has been found to be the best for most crop plants.

Optimum reaction for azotobacters of different species may vary. From their study of a number of Bavarian soils, Niklas and co-workers (Ger., 1926) have found that, although the natural occurrence of azotobacters is governed largely by soil reaction, many soils, despite their favorable reactions and lime content, contain no azotobacters, owing to deficiency of phosphorus.

Aëration and soil population. Air supply is another important factor concerned in modification and control of the soil microflora, as may be indicated by the opposite soil conditions regarding aëration under which nitrification and denitrification take place. Poor aëration tends to depress the activities of the favorable micro-organisms.

The oxygen supply may be regarded as one of the principal reasons why the activities of most of the beneficial soil organisms take place in the upper soil layer (15 to 20 inches deep) of arable soils.

Control of nitrification may be materially affected by compactness of soil materials. On fertile soils some farmers have experienced excessive lodging of oats and barley on spring-plowed lands,

whereas on the same lands, fall-plowed, no lodging or very little takes place. The explanation of the better results of fall-plowing lies in the fact that compactness of the seed bed retards nitrification. In loose, well-aërated, spring-plowed soils excessive nitrates form in highly productive soils, which causes rank and succulent growth of the small grains.

On many fields and in orchards, nitrification in soils continues after crops are harvested or after the need for available nitrogen has passed. No economical way has been found to check this process, although cover crops can be used to conserve the available nitrogen for succeeding crops (Ch. 18).

When microbial activities in a soil are changed, because of exclusion of soil air by water of saturation, deficiency of available nitrogen may be corrected most quickly through the use of nitrate fertilizers.

Addition of organic matter affects soil organisms. Whenever carbon-rich organic materials that contain less than 2 percent nitrogen are added to soils and turned under shortly before planting, some nitrogen fertilizer like nitrate of soda, sulphate of ammonia, and urea should be used to avoid depression of nitrates or starvation of the crop plants for nitrogen (Ch. 18).

Fertilizers and soil micro-organisms. Increasing soil acidity through continual use of acid-forming fertilizers makes soil conditions less and less favorable for the beneficial soil micro-organisms. The acidity may be neutralized by agricultural lime (Ch. 17).

Phosphorus compounds greatly accelerate the activity of nitrogen-fixing bacteria, especially azotobacters which require considerable quantities in their metabolism.

Composting or rotting of coarse organic matter or strawy manures before they are added to soil favors proper microbial activities after their application. This is particularly recommended in gardening and in the growing of truck crops.

Control of parasitic organisms. Slime fungus (*Plasmodiophora brassicæ*) which causes clubroot, or finger-and-toe, of cabbages and turnips can be controlled by the use of quicklime (CaO). Black root rot of tobacco may be kept under control when soil acidity is maintained between pH 4.8 and 5.6. And potato-scab fungus (*Actinomyces scabies*) may be controlled when soil acidity is maintained between pH limits of about 5 and 5.4.

On soils infested with potato scab, sulphur and sulphate of am-

monia may be used to change the soil reaction toward acidity, to within the desirable range for scab control. Among other measures for the control of disease organisms may be named soil sterilization, crop rotation, removal or burning of vegetable refuse, and prompt removal of all disease leaves and branches and dead or dying plants.

Partial sterilization of soils. It has been known for some time that partial sterilization of soils increases their producing power. The changes effected are mainly biological. This treatment of soils has been adopted in greenhouse cultivation, by growers of tomatoes and cucumbers in England, and by growers of tobacco in America, particularly for tobacco beds. For this treatment, steam is commonly used.

Cropping and soil micro-organisms. It is possible to starve out certain soil parasites by ensuring that they do not come in contact with the particular crops or plant tissues on which they grow and multiply. This involves either change of crops or a system of crop rotation. One of the great values of crop rotation consists in the effect that it has in tending to check the development of certain soil parasites, such as nematodes and organisms that cause clubroot on cabbages and turnips.

Growing plants affect soil micro-organisms in various ways. They probably constitute the most important factor in the distribution of soil microfloras. Starkey (1929) has found that different plants produce different effects in this respect, legumes versus nonlegumes, for example. His results indicate that plants may be a major factor in determining so-called "seasonal fluctuations of soil population," particularly in cases where variations are not due to temperature and moisture factors.

Moisture supply and micro-organisms. A close relationship exists between soil moisture and micro-organisms and their activities, but practical modification or control of these organisms through water relations may be effected only to a limited degree, as through land drainage, conservation of soil moisture, and irrigation. Optimum moisture conditions for the soil microflora are reached when about half the pore space of a soil is occupied by water.

Considerable quantities of salts may be present in some irrigation waters; these may adversely affect the beneficial soil micro-organisms and favor the development of actinomycetes. Greaves (1928) has found that in Utah nitrogen-fixing bacteria are much

more resistant to soluble salts than are other beneficial soil micro-organisms.

Inoculation of soils with beneficial organisms. Inoculation of legumes has already been discussed. Various beneficial micro-organisms may be added to soils for the growth of nonlegumes. This inoculation may be accomplished through the application of stable or barnyard manures and composts. If properly cared for or prepared, these materials are rich in bacteria; and when they are applied to soils, there are introduced at the same time various beneficial micro-organisms. On some newly cultivated peat and muck soils, light applications of good stable manure have proved to be exceptionally beneficial, as compared with liberal applications of inorganic fertilizers.

From their studies of azotobacters of three different species, Brown and Hart (1926) suggested that the inoculation of certain soils with these free-living nitrogen-fixing micro-organisms might prove to be beneficial in crop production.

Soil flora and soil structure. In recent years considerable attention has been given to soil micro-organisms as factors in the development of soil structure. The findings of Hubbell and Chapman (1946) have far reaching significance. Working on two calcareous, irrigated soils of southwestern United States, they found that bacteria, actinomycetes, and fungi formed distinct water-stable soil aggregates. Aggregation was effected by secretions from the cells of these organisms and by fungal hyphae; and the aggregates were compounded by the roots of grass (sudan).

These investigators suggested that loss of soil structure may result from the destruction of those conditions that favor the growth of soil micro-organisms and that remedial measures probably lie in the restoration and control of those soil conditions that are favorable to the soil flora.

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REVIEW QUESTIONS

1. In soil management, what microbial activities are involved? What is the relationship of these activities to crop plants?
2. Explain the difference between decomposition and mineralization of soil organic matter. Between microbial assimilation of soil nitrogen and fixation of atmospheric nitrogen by rhizobia (bacteria).
3. May ammonification take place in soils independently of nitrification? Explain.
4. Discuss the competition between crops and soil organisms for nitrogen. What significance have these facts in practical soil management?
5. What is meant by "ammonia toxicity" in relation to plant growth? Explain the cause and give remedy.
6. How does the work of azotobacters differ from that of nitrobacters? What are nitrifiers?
7. How rapidly do nitrates form in soils?
8. Has any correlation been found between rate of nitrification and need of crop plants for nitrogen? State the findings.
9. What causes the excessive loss of soil nitrogen immediately following the breaking of virgin soils for cropping? Can this loss be controlled?
10. How much nitrogen may be added to a soil by rhizobia? By azotobacters?
11. What is meant by "cross inoculation," in regard to rhizobia? Give examples.
12. Compare the relationship between soil reaction and the activity of soil organisms with the relationship between soil reaction and the growth of crop plants. (See also Ch. 15.) Discuss the control of soil microorganisms in relation to crop production.

CHAPTER 20

PLANT NUTRIENT ELEMENTS

Thus far we have discussed six of the eight principal factors that determine soil fertility—tilth, soil water, air, soil reaction, organic matter, and micro-organisms. We now come to a consideration of the "plant nutrient elements" regarding which agricultural literature is so voluminous, owing to the economic importance of the fertilizing elements and the enormous research work that has been done on soil fertility and plant physiological processes.

Because of the vast accumulation of knowledge regarding the plant nutrient elements, it will be convenient to divide the subject into four principal divisions, as follows: (1) underlying principles of fertilizer practices (Ch. 20); (2) fertilizers, or materials that are used to supply plants with available nutrient elements (Ch. 21); (3) the effects of fertilizers on soils and crops (Ch. 22); and (4) fertilizing crop plants to meet their nutrient requirements (Ch. 23).

Development of fertilizer practice. Adding substances to cultivated lands to increase their fruitfulness was practiced many centuries before a scientific explanation of the function of such substances was attempted (Ch. 1). The development of fertilizer practices in husbandry followed the breaking of new land and exhaustive cropping.

Although the use of farm manures is probably as old as agriculture and ancient treatises give considerable information on substances like wood ashes, marl, and refuse materials for increasing the fruitfulness of the ground, scientific fertilizing of crops did not begin until after Lawes (Eng.) began the manufacture of chemical fertilizers in 1843 and after the successful introduction of Peruvian guano into England in 1841, into Germany in 1842, and into the United States in 1844.

Materials used to supply nutrients. The principal materials commonly used to increase soil productivity are animal or stall manures, green manures, crop residues (like roots and straw), com-

mercial fertilizers, and agricultural limes. The term "commercial fertilizer" means fertilizing materials that have become articles of commerce. The term "chemical fertilizer" is commonly used to designate commercial fertilizers that are prepared through chemical processes. Agricultural limes improve soils in other ways besides supplying available calcium and magnesium (Ch. 27).

Snow as fertilizer. The French peasants have a saying to the effect that a fall of snow in February is worth a pile of manure. In other places snow is called "poor man's manure." That these sayings are based on observed facts has been shown by Jacques (Fr., 1920) who has found that snow in France is always richer than rain in both nitric acid and ammonia. In other places this fact may not hold. Shutt and Hedley (Can., 1925) found snow decidedly poorer in nitrogen than rain water, containing only about half as much.

Specific meaning of availability. The term "availability," as applied to the nutrient elements, implies a definite relationship between the soil elements, on the one hand, and crop plants, on the other. The term means more than solubility of a compound in weak acids and simple absorption by plants; it also implies the action of roots on soil materials, or the absorbing power of plants. F. W. Parker (1928) has shown that organic phosphorus in soil solutions, although soluble, is not used by crop plants at all, and McGeorge (1931-1933) has shown that in alkaline soils of Arizona, solubility of phosphates is not a measure of the availability of phosphate. The soil-chemistry commission of the International Society of Soil Science (1927) has agreed to use the term "available" only in cases where plant physiological evidence proves the absorption and assimilation of the elements concerned.

How plant growth may be increased. Inasmuch as water, carbon dioxide, and nutrient elements constitute the raw materials out of which plants manufacture their foods (Ch. 9), increase in plant growth may result by applying any of these materials when the soil supply is limited. Furthermore, if energy (sunlight) is limited, as in half-shade, growth of green plants may be increased by providing more light.

Limiting factors in plant growth. Any factor that may limit plant growth, because of deficiency, absence, or unfavorable condition, may be regarded as a limiting factor in crop production—it

may be sunlight, tilth, moisture, soil aëration, soil reaction, organic matter, beneficial micro-organisms, carbon dioxide, nitrogen, phosphorus, potassium, calcium, magnesium, iron, manganese, boron, silicon, or copper. When all factors are favorable, maximum yields result; but if one is deficient, the yield will be reduced accordingly (Ch. 10). Usually, however, a low yield is the result of more than one limiting factor. Available nitrogen is commonly a major limiting element, likewise available phosphorus. Furthermore, what may constitute a major limiting factor for one crop may not necessarily be a major limiting factor for another—soil acidity, for example.

Investigation of conditions and factors that cause outstanding yields on some farms or in certain fields would constitute constructive inquiry into the problem of what might be regarded as normal soil-fertility limits in a given locality or section. A low-lying field to which liberal applications of fertilizers are made may, for a period of years, produce an average yield of 150 bushels of Indian corn per acre, owing to an unfailing supply of favorable underground water. It would be poor economy to apply fertilizers as liberally to an upland field if the normal water supply from rains is adequate for yields of only about 65 bushels of corn per acre.

Law of the minimum. Liebig laid much emphasis upon the limiting nutrient elements when, in 1840, he formulated the so-called "law of the minimum" as applied to plant nutrition (Ch. 1). This statement implies, according to Liebig's own interpretation (1863), that nutrient elements are absorbed in certain definite proportions and in such manner that when the limit of one has been reached, absorption of the others is actually retarded or depressed. But Lagatu and Maume (Fr., 1919-1927) have found that, considering the three major nutrient elements (N, P, K), a deficiency of one may result in an increased absorption of the other two.[1]

Law of diminishing returns. Malthus used the so-called "law of diminishing returns" as the basis of a prophecy regarding growth of population; but as a prophecy, it thus far has not been fulfilled. Liebig was the first investigator to apply the "law" to crop production.

1 THOMAS, W. BALANCED FERTILIZERS AND LIEBIG'S LAW OF THE MINIMUM. Science, Vol. 70, No. 1816, p. 382. 1929.

The modern statement of the law, as applied to agriculture, was formulated by Marshall (Brit.) in 1890, as follows: "Whatever may be the future development of the arts of agriculture, a continued increase in the application of capital and labor to land must ultimately result in a diminution of the extra produce which can be obtained by a given extra amount of capital and labor."

Applying the "law" to crop production, Evans (1930) has formulated the following statement: "If a certain value in labor, fertilizer, or material be applied to an acre of land, it may be more than recovered in the value of the produce. Further applications give a produce increase not in equal proportion to the former yield, and so on till the value of the last-added agent just balances that of the added product." This statement, as applied to the use of fertilizers, may be illustrated by the following increases in yields of timothy and wheat, which were obtained from the use of nitrogen fertilizers:

DIMINISHING RETURNS OF TIMOTHY FROM NITROGEN FERTILIZER
(Ohio Agr. Expt. Sta., 1924-5-6)

Quantity of Nitrate of Soda Applied per Acre	Total Increase in Yield per Acre	Diminishing Returns from Successive 40-Pound Units of Nitrate of Soda
Pounds	*Pounds*	*Pounds*
40	282.0	282.0
80	527.0	245.0
160	758.0	231.0
320	911.5	153.5

The data in the last column of the table show that the first 40-pound increment of nitrate of soda gave a return of 282 pounds of timothy, and the fourth increment, 153.5 pounds.

DIMINISHING RETURNS OF WHEAT FROM THE USE OF NITROGEN
(Rothamsted, Eng., 1852-1864)

Soil Treatment (Annually)	Quantity of Nitrogen (N) Applied per Acre	Average Yields of Wheat per Acre	Average Diminishing Returns from Successive 43-Pound Units of Nitrogen
	Pounds	*Bushels*	*Bushels*
Minerals only (P, K, Mg, S, Na)	None	18.3	——
Minerals plus ammonium salts...	43	29.6	10.3
Minerals plus ammonium salts...	86	37.1	9.4
Minerals plus ammonium salts...	129	39.0	6.9
Minerals plus ammonium salts...	172	39.5	5.3

The Rothamsted results show that the returns from the fourth 43-pound increment of nitrogen returned only about half as much wheat as the first increment.

Another illustration of diminishing returns from fertilizers may be taken from data compiled by Spillman (1924), as follows:

DIMINISHING RETURNS OF COTTON FROM COMPLETE FERTILIZERS

Quantity of Fertilizer Used per Acre	Increase in Yield of Seed Cotton per Acre	Increase from 200-Pound Unit of Fertilizer	"R" Percentage Increase Above That of the Next Lower Increment of Fertilizer
Pounds	*Pounds*	*Pounds*	*Percent*
200	102.5	102.5 (a)	—
400	187.5	85.0 (b)	83.0
600	250.0	62.5 (c)	73.5
800	295.0	45.0 (d)	72.0
1,000	327.5	32.5 (e)	72.2

Mitscherlich (Ger., 1909-1911) has discovered that the relation between crop yields and quantities of a growth-increase factor (fertilizer, for example) is not a straight-line relationship, as Liebig had supposed, and that it may be expressed more truly as a logarithmic curve, expressed mathematically by the following equation:

$$y = A\ (1 - e^{-cx})$$

In this equation "y" stands for the yield obtainable with a definite quantity of "x" (fertilizer); "A" stands for the maximum yield obtainable with large quantities or excess of "x"; "e" is increment in yield; and "c" is a constant (percentage increase above that of the next lower increment of fertilizer). (Fig. 87.)

In its relation to a required fertilizer, the Mitscherlich equation is supposed to express the law of diminishing returns, as follows: The increase in yield produced by a unit increment of fertilizer is proportional to the difference between the actual yield obtained with a given fertilizer increment and the maximum yield obtainable. Mitscherlich found that the increase in yield resulting from a first unit quantity of fertilizer is greater than that which results from a second (equal) unit increment; the increase from the second unit is greater than that from the third unit increment; and so on.

Spillman (1930) [2] found that the law of diminishing returns may be expressed as follows:

$$y = A\ (1 - R^x)$$

2 SPILLMAN, W. J. A NEW BASIS FOR FERTILIZER EXPERIMENTS. Science, Vol. 71, No. 1831, p. 135. 1930.

In this equation "y," "A," and "x" have the same significance as they have in the Mitscherlich equation, while "R" is the ratio of a decreasing geometric series whose terms are the increments of "y," or increases in yield from successive equal increments of fertilizer. (See values in last column of preceding table showing

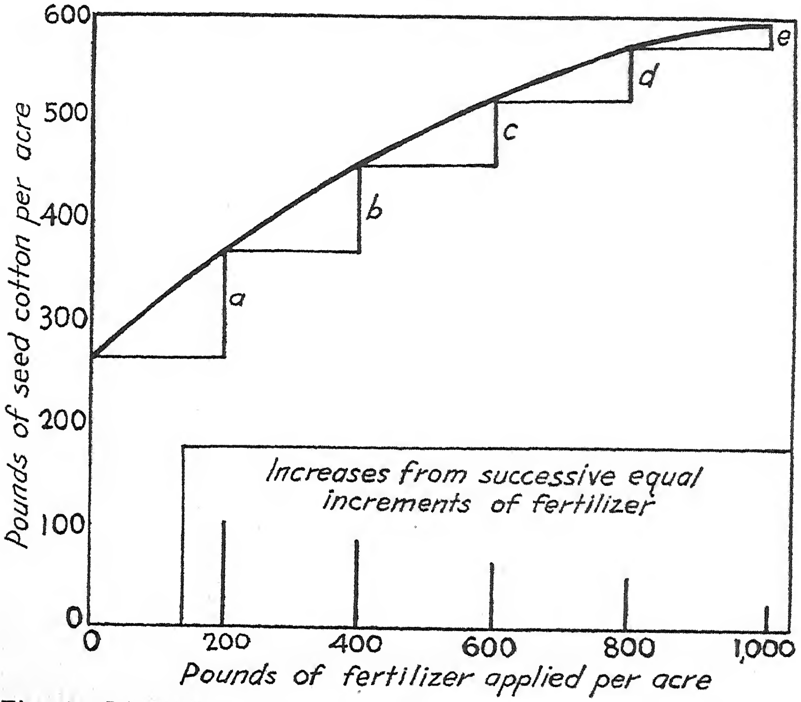

Fig. 87. Diminishing returns of seed cotton from successive equal increments of complete fertilizer, shown by "a," "b," "c," "d," and "e."

diminishing returns of cotton, derived from values in the third column.)

The serial relationships represented by Spillman's "R" are shown in Figure 87; these relationships are based on the increases in seed cotton given in the previous table. The ratios that constitute a decreasing geometric series are b to a, c to b, d to c, and e to d. The "R" has the same significance as the "e^{-c}" of the Mitscherlich equation.

Some experiments indicate that when increments of fertilizer are not too large, returns may increase at first in a greater proportion

than the quantity used, and that not until a certain excess is applied do the returns begin to diminish from equal increments.

Fertilizing plants with carbon dioxide. In 1804, De Saussure not only showed that green plants draw on the small quantity of carbon dioxide normally contained in the atmosphere, but also that they can use more when it is available (see Index). As a means of increasing the efficiency of crop plants, application of this was not made until World War I, when, under pressure of food shortage, Riedel and co-workers (Ger.) perfected processes that make possible the utilization by greenhouse plants of carbon dioxide obtained from coal, coke, and charcoal. Increasing plant growth by enriching the air artificially with carbon dioxide may be designated as "fertilizing crops aërially."

Fertilizing plants with iron through their leaves. Plants require iron, an essential nutrient, in only small quantities; yet when there is a deficiency or when iron becomes immobile or inactive within plants, chlorosis, or yellowing of the leaves, results. Gris (Fr., 1843-1847) discovered that when he applied iron sulphate (copperas) to leaves or roots of chlorotic plants, they became green. Since that time, applications of iron have been made to chlorotic plants by spraying their leaves with weak solutions of iron salts or by injecting iron salts or solutions of them into the branches, trunks, or roots, as of trees. Johnson (1924) found that chlorotic pineapples on manganiferous soils of Hawaii may be effectively and economically corrected by spraying the plants when they are small at intervals of from 1 to 4 months with a weak solution of iron sulphate (25 lb. to 50 gal. water, solution applied at rate of 20 gal. per a. at each treatment). This has become a common practice in Hawaii, for it has proved to be impracticable to correct the soil condition or to supply sufficient available iron through the use of iron-containing fertilizers. Sugarcane on coral soils is treated in a similar manner for Pahala blight.

Major nutrients v. the trace essentials. Not long after the systematic inquiry into plant nutrition began (following 1843), nitrogen, phosphorus, and potassium were recognized as major plant-food elements. These three nutrients have been given primary consideration for many years, and they have determined the chemical constitution or fertilizing constituents of commercial fertilizers and fertilizer materials.

Ten elements—nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, carbon, hydrogen, and oxygen—have been considered necessary for crop production. The first three nutrient elements were regarded as sufficient to supply deficiencies in practically all kinds of soils, but modern research has shown that large areas of soils may be deficient in available calcium, magnesium, iron, sulphur, manganese, and in places, in copper and probably boron.

Magnesium deficiency is usually indicated by a chlorotic condition of the leaves. Magnesium hunger in tobacco is known as "sand-drown," in which breaking down of both green and yellow chlorophyll pigments begins at the tip of the lower leaves and progresses toward the base, resulting in a bleached appearance of the leaves (Fig. 5). Magnesium-deficiency symptoms in tobacco are more prevalent in wet seasons and on sandy soils, hence the name "sand-drown."

Crop plants grown on light or leachy soils, on exhaustively cropped soils, and in the absence of magnesium in fertilizers used are subject to magnesium hunger. Magnesium may be regarded as a valuable constituent of commercial fertilizers, particularly when used on light soils that are deficient in this element.

In general, from about 15 to 60 pounds of water-soluble magnesium (Mg) to the acre, or the equivalent of about 75 to 300 pounds of pure magnesium sulphate, is sufficient to meet this deficiency in soils. From 200 to 250 pounds of pulverized dolomitic limestone per acre, analyzing 20 or more percent magnesium, may also be applied for this purpose. For control of sand-drown in growing tobacco on magnesium-deficient soils, from 500 to 1,000 pounds of dolomitic limestone or from 100 to 200 pounds of sulphate of potash-magnesia (analyzing about 6.5 percent magnesium) may be applied per acre, either singly or mixed with the fertilizer used.

On some strongly acid and long-cropped potato soils of Maine, on which "potato sickness" has developed, Chucka (1931) has reported increases in yields of from 3.2 to 36.1 bushels an acre from applications of 100 pounds of magnesium sulphate (10.3 lb. Mg).

Inasmuch as magnesium seems to function as a carrier of phosphorus in plant metabolism (Ch. 10), proper assimilation of phosphorus by crop plants cannot take place when available magne-

sium is deficient or lacking, even though adequate available phosphorus may be present. Thus, in crop production, a deficiency of available magnesium in soils has an important bearing on phosphorus problems, as suggested by Kellogg (1931) regarding soils of semiarid regions, by Brioux and Jouis (Fr., 1931) in pot tests, and by Truog (1931) as affecting the fertilizing value of rock phosphate.

The use of dolomitic agricultural limes may prove to be distinctly beneficial on acid soils which are apt to show deficiency of available magnesium or to develop unbalanced calcium-magnesium balance (Ch. 17) when treated with calcium carbonate or calcitic limestone. Such soils are those of the Atlantic Coastal Plain.

Iron-nutrition problem in plants is commonly indicated by chlorosis, caused by (a) intake of excessive lime, which renders iron inactive, as in Hawaiian pineapples, established by McGeorge (1923, 1926), (b) unavailable iron, as in strongly alkaline soils, and (c) reduction of acidity of cell sap due to breakdown of organic acids by intense sunlight and heat, thus decreasing soluble iron, as shown by several investigators. In meeting this iron problem, iron sulphate may be sprayed on leaves, injected into plants, or applied broadcast or in small holes punched into the ground, as around trees and shrubs. Soil iron may be rendered available through the use of acidic fertilizers and also sulphur. Wallace (Eng., 1929) described "grassing down" of orchards for 3 years with alfalfa, clover, or grasses, and fertilizing with sulphate of ammonia.

Sulphur requirement of crop plants varies widely, depending on the kind of crop, as is shown by the figures, based on data published by Hart and Peterson (1911), in the table on p. 382.

In addition to the quantity removed by crops, sulphur is constantly being leached from soils, in amounts varying from 13 to 80 pounds per acre annually.

Sources of sulphur for agricultural crops include soil minerals and organic matter, the atmosphere, fertilizers, and materials used in spraying fruit trees, such as sulphuric mixtures, dust, etc.

The soil content of sulphur (S), to a depth of 6 or 7 inches, varies from 0.01 to 0.09 percent, and in quantity it may vary from 160 to 828 pounds in Maryland soils, from 400 to 1,200 pounds in Wisconsin, from 719 to 938 pounds in Iowa, from 360 to 1,000 pounds in Kentucky, from 252 to 1,764 in Utah, from 140 to 1,100

QUANTITIES OF SULPHUR REMOVED BY HARVESTED CROPS, AS COMPARED WITH PHOSPHORUS

Crop	Yield per Acre	Quantity of Phosphorus (P) Removed per Acre	Quantity of Sulphur (S) Removed per Acre
		Pounds	*Pounds*
Alfalfa (hay)	4.0 tons	19.0	21.0
Barley, grain	40 bu.	7.0	2.6
straw	1 ton	2.0	3.1
Total		9.0	5.7
Cabbages (heads)	15 tons	9.5	21.8
Clover, red (hay)	2 tons	10.0	6.2
Corn (maize), grain	65 bu.	9.0	5.7
stalks and cobs	2.2 tons	7.5	5.0
Total		16.5	10.7
Oats, grain	50 bu.	6.0	3.3
straw	1.25 tons	2.5	5.4
Total		8.5	8.7
Potatoes (Irish), tubers	200 bu.	8.5	3.5
Sugar beets, roots	15 tons	10.5	5.3
leaves (green)	6.2 tons	6.5	6.5
Total		17.0	11.8
Tobacco, leaves	1,500 lb.	3.0	5.3
stalks	1,250 lb.	2.5	1.0
Total		5.5	6.3
Turnips, roots	15 tons	12.0	20.8
leaves (green)	5 tons	4.0	13.8
Total		16.0	34.6
Wheat, grain	30 bu.	6.5	2.6
straw	1.6 tons	2.5	3.7
Total		9.0	6.3

pounds in Oregon, and from 246 to 712 pounds per acre in the eastern part of Washington State.

Sulphur in considerable quantities is brought down from the atmosphere in rain and snow. At Rothamsted, England, it amounts to about 7 pounds per acre annually; at Lincoln, N. Z., 6 pounds; in Virginia, 17 pounds; in New York State, from 24.6 to nearly

36 pounds; in Kentucky, 36 pounds; in Texas, from 4 to 12 pounds; in Wisconsin, from 6.8 to 7.2 pounds; in Utah, from 6.4 to 32.7 pounds; and in Washington about 5.5 pounds per acre.

Where tested, crops on most soils in the world have shown no appreciable response to sulphur as gypsum. Exceptions include certain basaltic areas of the northern Pacific Coast States, where increases in yields of alfalfa have been obtained in experiments with sulphur, and also parts of Nyasaland, East Africa.

It is possible that the use of concentrated chemical fertilizers, which contain little or no sulphur, may cause a deficiency of sulphur in certain soils, especially for crops liks alfalfa, cabbages, onions, and cotton. Cotton requires considerable sulphur, inasmuch as a 500-pound cotton crop (lint) removes about 18 or 20 pounds of this element (S), as compared with about 10 pounds of phosphorus.

Manganese is present in most soils in sufficient quantities to meet the comparatively small requirements of plants; but in certain districts or localities where soils are deficient in this element or where it is unavailable, serious effects have been produced on agricultural crops. Manganese deficiency in plants causes chlorosis in some plants and abnormal symptoms, analogous to diseased conditions, in others. According to Mazé (Fr., 1914), chlorosis in maize can be induced by depriving the plants of manganese as well as by depriving them of iron and sulphur.

The so-called Pahala blight of sugarcane may be caused by deficiency of either iron or manganese or both. Malnutrition due to a deficiency of manganese has been observed in vegetables and greenhouse crops and in oats and other farm crops in Australia, Europe, and the United States. Manganese deficiency in certain lime-rich soils of Florida was reported by Schreiner and Dawson in 1927. Here applications of 50 pounds of manganese sulphate or its equivalent in manganese-containing manures or composts have been found essential for successful production of tomatoes and other vegetables. On areas of marl soils south of Miami, without manganese, even with 2-ton applications of complete commercial fertilizer, tomato plants soon became bleached or faded, and died (Figs. 6 and 88).

Throughout the eastern part of North Carolina, unproductive spots have been found in cultivated fields on which corn and soybeans showed symptoms of manganese hunger. The soil reaction

in these spots varied from pH 6.2 to 7.4, resulting from excessive use of lime. Chlorosis of the soybeans can be completely obviated through the use of manganese sulphate. At the Rhode Island Experiment Station, a lack of available manganese has always been found on plots that have been limed to produce a neutral or alkaline reaction. Zimmerly (1926) has reported chlorosis of spinach,

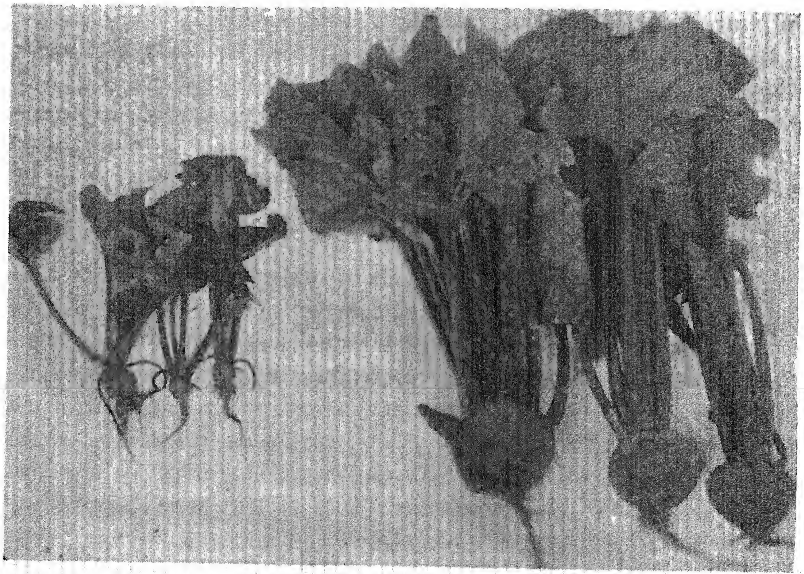

Fig. 88. Garden beets grown on a manganese-deficient, calcareous glade soil of Florida, liberally fertilized with complete chemical fertilizer. Left—Beets that received no manganese. Right—Plants that received 50 pounds of manganese sulphate per acre. (Bur. Chemistry and Soils, U. S. Dept. Agr.)

resulting from manganese deficiency, on the lighter-textured *Norfolk* soils of the Atlantic Coastal Plain. According to Conner (1932), certain nonacid black loams of low areas in northeastern Indiana on which oats have failed to yield well have been found to lack available manganese. Correction for this condition may consist either in applying available manganese or in adding materials that develop acidity. Organic soils may lack manganese.

Boron has a favorable effect on plant growth only when present in very small quantities—from 1 to 2½ parts per 5 million parts of solution. As little as 5 parts per million has been found toxic for potatoes, and 5.5 parts has injured tomatoes. For some crop

plants, boron is needed for healthy growth, as preventing nutritional disorders in citrous and leguminous plants, heart and dry rot in sugar beets and mangels, brown heart in rutabagas and turnips, corky core in apples, browning of cauliflowers, cracked stem of celery, and "top-sickness" of tobacco. Haas (1930) suggested a probable boron deficiency in some California citrous orchards, since symptoms have been observed in these orchards similar to those produced artificially in boron-deficient sand cultures.

The use of boron in crop production is probably not generally necessary, except in certain localities and on leachy sandy soils on which boron-free fertilizers may be continually used. However, where boron is deficient, borax may be used at the rates of from 5 to 15 pounds per acre in drillrows to 30 or 80 pounds broadcast.

Copper is included in the group of elements essential for plant growth. Like boron, it is required only in very small quantities. Spraying potatoes, citrous, and other crops with bordeaux mixture, which contains copper, has effected improvement in plant growth as well as control of diseases.

Allison and co-workers (1927) and Bryan (1929) have reported positive growth responses from external applications of copper and manganese on chlorotic crop plants (including cowpeas, beans, and sorghum) on raw peat soils of the Florida Everglades. Applications of from 20 to 50 pounds of copper sulphate per acre seem to be the best treatment to meet this deficiency. Other investigators have reported productive responses of crop plants on certain peat soils from spraying with bordeaux mixture, a fungicidal mixture composed of copper sulphate, lime, and water.

Deficiencies of copper and iron in certain sandy soils of Florida are associated with the development of "salt-sick" in cattle that feed on the native herbage of these soils.[3]

Chlorine, although not regarded as an essential nutrient element, occurs in practically all plants. It has been found to stimulate some crop plants. Garner and co-workers (1930) have published data showing that on light sandy and sandy-loam soils a moderate supply of chlorine in fertilizers commonly stimulates the growth of tobacco plants. The increase in yield therefrom has averaged about 10 percent. From 20 to 30 pounds of chlorine (Cl) per acre, or the equivalent of from 42 to 63 pounds of pure potassium chloride or muriate of potash, has proved to be sufficient to produce maxi-

[3] BECKER, R. B., NEAL, W. M., and SHEALY, A. L. SALT-SICK: ITS CAUSE AND PREVENTION. Fla. Agr. Expt. Sta. Bull. 231. 1931.

mum stimulating effects. One of the effects of chlorine in soils consists in rendering magnesium available.

The trace essentials in plant and animal nutrition. Results of modern inquiry into plant and animal nutrition point to the fundamental significance of the presence of trace-essential elements in plants and animals. Remington and Shiver (1930) have found iron, manganese, and copper in the leaves and shoots of a large number of vegetables and fruits in quantities ranging from 8.2 to 682 parts per million.

Manganese, copper, boron, iodine, zinc, nickel, and cobalt occur in animal bodies. Manganese has been found in greatest concentration in marine and fresh-water mollusks, including oysters and mussels. Copper is a normal constituent of animal bodies, being present in larger quantities in the liver than in other organs. Appreciable quantities occur in yolks of eggs and in cream. Oysters are rich in copper.

Freedom from certain human and animal diseases as well as from certain plant diseases may depend on the absorption of these trace essentials by plants and their presence in human and animal foods. *Iodine,* for example, has been found highly beneficial to both humans and animals as a constituent in their food. It has proved to be essential in the prevention of human goiter, abortion in cattle, and hairlessness in young pigs. The importance of copper in the treatment of pernicious anemia may also be mentioned.

According to McHargue (1927), the soils of the bluegrass region of Kentucky are richer in copper, manganese, zinc, nickel, and cobalt than those of other parts of the State. In this region the bluegrass makes a luxuriant growth because it can obtain all the elements that are necessary for growth. Accordingly, it is believed that the grass here constitutes an adequate source of all those substances that make possible the development of the high-quality livestock for which the bluegrass region is famous.

Some elements absorbed by plants may not benefit animals, but poison them instead; for example, in some places on western ranges, selenium has poisoned grazing animals.

Absorption and assimilation of nutrients. If definite information were available regarding absorption and assimilation of nutrient elements by plants, it would probably lead to more efficient and economical use of some fertilizers, and to the elimination of

certain other fertilizer materials. Very little is definitely known regarding the forms in which the elements are absorbed or about the mechanics of absorption.

Evidence indicates that the reaction of the mediums in which plants grow may affect the physiological condition within plants, which, in turn, may affect absorption of the essential nutrients. The ability of certain plants to absorb and assimilate ammonium nitrogen normally when growing in neutral or near-neutral mediums, and their inability to do so in acid mediums, typically illustrates this point. With some plants, a similar phenomenon seems to occur with reference to the absorption and assimilation of iron, as Rogers and Shive (1932), Willis (1932), and Shive (1932) have suggested. Rogers and Shive found no accumulations of iron in plants whose tissues throughout showed low pH values (acid).

Under natural or field conditions, nitrogen is probably absorbed by most plants principally as oxidized nitrate ions (NO_3). Probably phosphorus is also absorbed mostly in the form of highly oxidized ions, owing to the oxidizing action of the absorbing parts of roots. The absorption phenomenon raises the question of so-called "selective absorption" or differential absorption of essential ions.

Garner and co-workers (1930) found that potassium applied to tobacco as sulphate was quite as readily absorbed by the plants as that applied as chloride; but while only a comparatively small proportion of the sulphate ions (SO_4) was taken in, the chlorine ions were readily absorbed.

Casale (It., 1921) has suggested that nutrition of plants is probably an electrical phenomenon, in that plants absorb nutrient elements in the form of ions that are known to be mobile and to carry plus charges to satisfy negatively charged colloids within. According to a similar theory suggested by Breazeale (1923), the demand of a plant for a negatively or positively charged ion like $H_2PO_4^-$ or K^+, for example, originates within the plant and is transmitted to the absorbing zones of the roots as an unsaturated, positively or negatively charged colloidal organic complex which finally attracts negatively or positively charged ions of the soil mass. When the demand is met by properly charged ions, definite chemical compounds are formed within the root cells.

Absorption is not simply the passing of substances through membranes according to the chemical law of mass action and equi-

librium. On the contrary, the activities of living cells are involved. Absorption is an exceedingly complex phenomenon which, according to McGeorge and Breazeale (1931), is dependent on soil conditions that favor the development of roots; this development, in turn, stimulates enzymatic and chemical oxidizing reactions, thereby causing a generous exudation of carbon dioxide by the roots. Thus one can see that the complexity of the processes involved, within and without the plant, has given rise to many theories. However, evidence indicates that the absorption of nutrients is not determined by the intake of water; and that in the close contact between roots and soil colloidal matter, according to Jenny and Overstreet (1939), exchange of ions between clay and roots might occur without their first entering the soil solution.

Nutrients of fertilizers, and availability. Several factors may affect the availability of nitrogen, phosphorus, and potassium after fertilizers are applied to soils; these factors include moisture, tilth, aëration, soil reaction, base-exchange, micro-organisms, organic matter, and the feeding systems of plants. Fertilizing a crop does not mean simply incorporating into the soil a certain material on which the plants are to feed. On the contrary, *adding fertilizing material to a soil results in physical, chemical, and biological actions and reactions.* In a soil, complex as it is, the plants may obtain the nutrients they require through the dissolving action of their roots and the action of forces within the plants and on the outside of their absorbing systems.

Carbohydrate-nitrogen relation in plants. Physiological conditions within crop plants may materially reduce the yield of produce even though the soil and other conditions may be favorable for optimum growth. With some agricultural plants like potatoes, tomatoes, and fruit trees, maximum growth may mean very low yields or no produce or fruit at all. Klebs (Ger., 1904-1918) has found that fruitfulness is determined by a certain relationship between carbohydrates and nitrogen compounds within the plants. This fact has been confirmed by Kraus and Kraybill (1918) in experiments with tomatoes. The economic significance of the carbohydrate-nitrogen relationship may be stated with reference to some plants as follows:

1. Plants in which the manufacture of carbohydrates is limited, even though the soils may contain abundant supplies of available nitrogen and

other nutrient materials, are neither vegetative nor fruitful. Overpruned apple trees are good examples; also defoliated plants.

2. Plants in which carbohydrates cannot accumulate because of much growth resulting from abundant supplies of nitrogen, other nutrients, and moisture, are highly vegetative, but unfruitful. These conditions may be illustrated by tomatoes that "run to vine," and by a young, vigorous, unfruitful apple tree growing in a very rich soil.

Restricting the supply of available nitrogen in any way—by cutting the roots, depressing nitrification, or temporarily neglecting tillage—may effect fruitfulness. A vigorous growing but fruitless tree or shrub can be made to bear fruit by checking the downward flow of organic materials in the plant through the use of girdles or by means of wire twisted tightly around the trunk or branches. It is known that the partial girdling of a thrifty, nonbearing fruit tree by rabbits may produce the same results.

3. Plants in which carbohydrates accumulate in abundance, and for which available nitrogen is lacking, are neither vegetative nor fruitful. This class of plants may be represented by an apple tree which was once fruitful but has since become unproductive, principally because of a deficiency of available nitrogen. Here the solution lies in applications of nitrogen fertilizer.

4. Plants that accumulate carbohydrates (excess over the amount required for growth) and that obtain adequate nitrogen and other materials are both vegetative and fruitful.

Low sugar content of sugar beets and sugarcane grown on soils that supply an abundance of available nitrogen may be traced to the relation between carbohydrates and nitrogen (class 2). Inasmuch as vegetative growth is not accompanied by accumulation of sugar, it is important that the nitrogen supply be controlled in order to stop growth in due season, so as to allow accumulation of carbohydrates (sugar).

Premature heading of crop plants like cauliflower may be caused by a high content of carbohydrates within the plants and a low content of nitrogenous compounds (class 3).

With flowering plants, a preponderance of nitrogen over carbohydrates leads to much vegetative growth and repressed flowering.

Root food reserves and vegetable growth. Root food reserves of a plant consist principally of carbohydrates and nitrogenous compounds which have been synthesized by the plant and stored in its roots for future use. Such reserves bear a most important relation to vegetable growth of alfalfa, clovers, grasses, and other perennial herbaceous plants. When other conditions are favorable, abundant food reserves usually mean vigorous growth.

When quackgrass (*Agropyron repens*), for example, is defoli-

ated, renewed growth is made possible by the reserve of food materials in the rhizomes underground. If each new growth is cut before replacement of food reserves takes place, the stored food will become exhausted, and the plants will die of starvation.[4] Any quantity of fertilizer, under such conditions, cannot increase growth. A plant cannot utilize available nutrient elements so long as it cannot manufacture food substances (Ch. 9). This explains why too frequent close cutting of lawn grasses proves to be injurious, especially when the grasses are those that do not bear many of their leaves close to the ground.

Bentgrasses—especially the creeping, Colonial, and velvet strains —can tolerate very close and frequent cuttings, owing to the fact that a large proportion of their leaves are borne close to the ground; hence their suitability for golf greens.

Pasture grasses that are continuously closely grazed gradually lose their root reserves of food, with consequent deterioration of the pasturage. The value of rotational grazing of pastures lies partly in allowing the grasses to renew their food reserves, partly in obtaining high-protein pasturage through fertilizing, and partly in lengthening the grazing period.

Graber and co-workers (1927) have reported reduced vigor and vegetable growth (yields) of alfalfa, timothy, bluegrass (*Poa pratensis*), and redtop (*Agrostis alba*), even on fertile soils, resulting from frequent close cuttings.

Willard (1931) has pointed out that alfalfa grown in nonhumid regions of the United States may be less commonly injured by frequent cutting than that grown in humid regions, because of less exhaustion of the roots. Alfalfa uses less synthesized foods for top growth and more for root growth when the weather is dry than when it is humid.

Permanent soil productivity. It would seem that permanent soil fertility could be developed in a given soil simply by maintaining in that soil a supply of nutrients adequate for productive yields that the supply of water will allow. Liebig believed that a soil could remain fertile so long as the elements removed were replaced by fertilizers. He emphasized particularly (1847-1851) the importance of the ash constituents of crop plants, for he believed that plants derived their nitrogen as ammonia from the atmosphere.

[4] WEIR, W. W. SOLVING THE QUACK PROBLEMS. Hoard's Dairyman, Vol. 59, No. 12. April 9, 1920.

But Liebig's Mineral Theory of permanent soil fertility, as expressed in his statement of the law of diminishing returns (Ch. 1), soon received its deathblow from Lawes and Gilbert (Eng., 1851) who showed by carefully conducted experiments that the German scientist was wrong. From experiments conducted at Rothamsted, Lawes and Gilbert (1855) concluded that soil productivity could be maintained only for a time by the use of artificial fertilizers.

Later on, supported by results of field tests, Ville (Fr., 1867, 1874-1875) taught that soil fertliity could be maintained only through the use of artificial manures which he thought were better than dung. Regarding nitrogen, phosphorus, calcium, and potassium as the dominant elements, he outlined simple field plot tests to enable farmers to find out for themselves what their soils needed. But his views regarding the sufficiency of chemical fertilizers did not survive.

In reference to the question of whether chemical fertilizers can maintain yields, it is interesting to note the comparable yields of wheat (yields for same year, compared) obtained on the Broadbalk and Agdell Fields at Rothamsted, covering the period 1851-1919, given in the following table:

COMPARABLE YIELDS OF WHEAT OBTAINED AT ROTHAMSTED [5]
(Acre Yields in Winchester or American Bushels)

YEAR OF COMPARABLE YIELDS	BROADBALK FIELD, CONTINUAL CULTURE		AGDELL FIELD, WHEAT GROWN IN A 4-YEAR ROTATION	
	Unfertilized	Complete Chemical Fertilizer	Unfertilized	Complete Chemical Fertilizer
	Bushels	*Bushels*	*Bushels*	*Bushels*
Harvest of 1851, the first year of comparable yields...........	16.38	33.22	29.41	29.80
Average yields for 4 years, 1851-55-59-63..................	17.67	33.46	34.35	39.25
Average yields for 5 comparable years, 1903-07-11-15-19......	10.40	21.69	15.62	22.34

The Rothamsted data on wheat and barley show that chemical fertilizers maintained yields for a time, but did not do so over a long period of years. Morris (1924) found that after 30 years of cropping, in a 5-year rotation, of maize, oats, wheat, clover, and timothy on silt loam of Wooster, Ohio, the soil suffered an average loss of 22 percent of its original supply of nitrogen, regardless of fertilizer treatments. White (1932) has given a summary of

[5] U. S. Dept. Agr. Dept. Bull. 1377, p. 14. 1926.

the relative crop yields obtained on some of the Jordan Soil-fertility Plots, with special reference to nitrogen, as illustrated in Figure 89.

In Illinois, Hopkins (1910) formulated certain precepts regarding permanent soil fertility which include the following points: (1) provision of total soil nitrogen adequate to meet the needs of maximum yields by growing legumes in rotation with other crops,

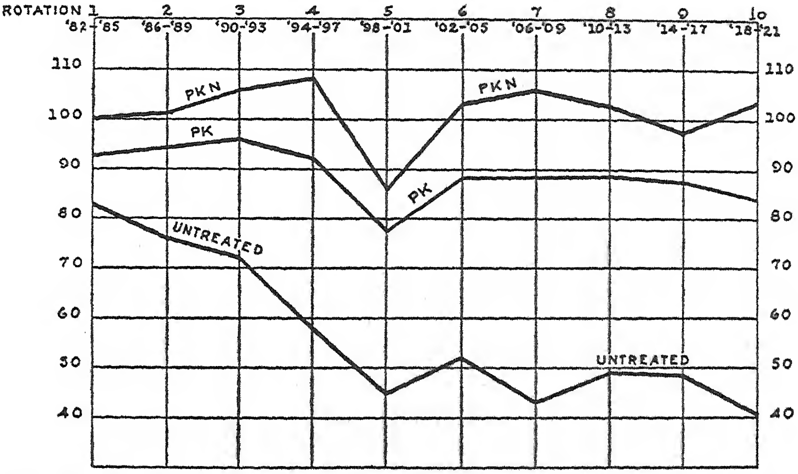

Fig. 89. Forty-year trends of relative crop yields on the Jordan Soil-fertility Plots (Pa.), based on 4-year-rotation periods. Yield of first rotation period obtained on plots receiving complete chemical fertilizer (PKN) is taken as the base relative (100). Crop rotation, coupled with the use of proper complete chemical fertilizer, may effect fertility maintenance.

returning crop residues, conserving farm manures and applying them to the fields, and by making use of cover and green-manure crops; (2) determination of the total quantities of calcium, magnesium, potassium, and phosphorus in soils and of their relation to requirements of crop plants, and provision of soils with adequate quantities of calcium, magnesium, and phosphorus through the use of limestone and rock phosphate; and (3) liberation of sufficient soil potassium for maximum crops, and improvement of certain potassium-deficient soils by applying potash fertilizers.

According to Agee (1930), rotating crops, returning crop residues, green-manuring, and fallowing for maintenance of soil productivity is practically unknown in Hawaii; yet the planters con-

tinue to produce enormous crops of sugarcane by maintaining in their soils adequate reserves of phosphorus and potassium, and by supplying sufficient nitrogen to meet current needs of crops—all of which, Agee says, can be done through the judicious use of proper commercial fertilizers.

In a general sense, the problem of permanent soil productivity is a rather difficult one, even under favorable conditions. Specifically, the problem is vague, owing to the fact that "maintenance of soil fertility" has no definite meaning. From both scientific and empirical points of view, "soil-fertility maintenance" can, at best, be interpreted only with reference to a given soil, a given crop, and a given environment. Moreover, economic factors come into play. But as references are commonly made to maintenance of soil productivity, even in scientific discussions, the concept of *permanent soil fertility,* although indefinite, remains with us.

Because of absorption properties of colloidal soil materials, mineral elements are not readily leached from most soils. Sandy soils, especially those consisting largely of sand, are readily leached, because they contain only small quantities of colloidal materials. The absorptive property of soils is a most important one, as it affects conservation of mineral nutrient elements and maintenance of soil productivity. This assumes the presence of topsoils, which are essential for organic matter. On many western ranges the absence of topsoils (eroded) hinders revegetation.

Evidence would indicate that, so far as the essential nutrient elements are concerned, nitrogen demands greatest attention in the maintenance of soil fertility. Even under good systems of soil management, the nitrogen content of soils may continue to decrease until comparatively low percentages are reached, indicating that meeting current needs of crops for this element seems of greater importance than maintaining a high percentage of *total* soil nitrogen.

Inasmuch as decline in crop yields results mainly from destruction of soil organic matter, decrease of available nutrient elements, development of soil acidity, destruction of favorable soil structure, and soil erosion, maintenance of soil productivity depends in a large measure on (1) maintaining adequate supplies of organic matter; (2) rational use of proper fertilizing materials; (3) proper adjustment of soil reaction; (4) maintaining favorable physical condition of soil materials; and (5) control of soil erosion.

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REVIEW QUESTIONS

1. Explain the meaning of the term "availability," as it is applied to nutrient elements in soils. What determines availability?
2. In what four different ways may plant growth be increased? Give examples.
3. Illustrate the "law" of diminishing returns in soil fertility.
4. Compare the problem regarding the plant nutrient sulphur with Liebig's idea of the nitrogen supply of crop plants.
5. Discuss the relation of the trace-essential plant nutrient elements to fertilizer practice and animal nutrition.
6. What theories have been advanced regarding the manner in which the nutrient elements are absorbed by plants?
7. What is the theory regarding carbohydrate-nitrogen relationship in plants? Illustrate.
8. Explain why, on golf greens, bentgrasses have the advantage over grasses that have upright growth habits.
9. What meaning is intended by the term "permanent soil fertility"?
10. Would it be possible to meet the nutrient requirement of crop plants through the use of organic matter only? Explain.

CHAPTER 21

FERTILIZERS

In a general sense, the term "fertilizer" includes any material that is used to increase the growth of plants or the yields of crops; but in agricultural literature, the meaning of the term is restricted to artificially prepared materials or those that may be obtained on the market for the purpose of supplying plants with nutrient elements, principally nitrogen, phosphorus, and potassium. The term "manure" is commonly used to designate materials like farmyard or stall manures, composts, and artificial farm manures.

Manures were used in agriculture probably more than 90 centuries before chemical and commercial fertilizers came into use (Ch. 1). In the United States, the first commercial fertilizers were manufactured in Baltimore in 1849. For many years England was the principal producer of superphosphate, sulphate of ammonia, and natural nitrate of soda, owing to the fact that she was the largest user of coal and had the largest interests in the nitrate fields of Chile.

Between 1804 and 1844, from the work of De Saussure, Liebig, Lawes and Gilbert, and others on nutrition of plants and fertilizing of crops, the sources of the most important nutrient elements—nitrogen, phosphorus, and potassium—became the basis for classifying the fertilizing materials as follows: *organic, nitrogen, phosphate,* and *potash*. Mixtures of these classes of materials are called "mixed" and "complete" fertilizers. These different fertilizers will be discussed in the order named.

ORGANIC FERTILIZERS

The most important organic fertilizers are farmyard manures which consist of solid and liquid excretions of farm animals, together with more or less bedding material and other litter. They are sources of organic matter as well as of nutrient elements. Farm manures have certain properties that are not shared by many chemical fertilizers.

The fertilizing value of farmyard manures varies widely, depending on kind and age of the animals, kinds of feeds used, absorption of liquid excrement, conservation, content of bedding material or litter, and stage of decomposition.

How animals and feeds affect manures. Fattening animals retain only about 5 percent of the nitrogen contained in the feeds used, whereas growing animals and milk cows utilize considerably more. Accordingly, manures that are produced in the care of fattening animals are richer than those obtained in the care of young animals and milk cows.

The comparative fertilizing values of manures produced in the care of different kinds of animals are indicated in the following table:

QUANTITIES OF FERTILIZING CONSTITUENT IN FRESH MANURES
(Including Solids, Liquids, and Bedding Materials)

KIND OF ANIMALS	AVERAGE PERCENTAGE OF WATER	QUANTITIES OF NITROGEN, PHOSPHORUS, AND POTASSIUM IN ONE TON				
		Nitrogen (N)	Phosphorus *		Potassium †	
			Element (P)	Equivalent as P_2O_5	Element (K)	Equivalent as K_2O
	Percent	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
Cows	78	9–10	2.5–3	5.7–6.9	6–8	7.2–9.6
Horses	63	10–15	2–3	4.6–6.9	8–14	9.6–16.8
Hogs	74	11–13	5–6	11.5–13.8	6–12	7.2–14.4
Sheep	63	27–34	3.5–5	8–12.5	20–23	24–27.6
Poultry (hens)	58	20	8	18.4	15	18

* Phosphorus $\times$ 2.3 = P_2O_5. $P_2O_5 \times 0.4366 = P$.
† Potassium $\times$ 1.2 = K_2O. $K_2O \times 0.83 = K$.

The kind of feed affects materially the fertilizing value of manures. Ordinarily, the richer the feed, the richer is the manure. Feeding wheat bran, for example, greatly increases the phosphorus content of the manure.

Fertilizing value of liquid manure. About 54 percent of the total nitrogen of manure and about 60 percent of the total potassium are contained in the liquid excrement. Inasmuch as the liquid excretion of animals contains most of the nitrogen and potassium that is eliminated from the digested part of feeds, the fertilizing value of manures is enhanced through absorption of the liquid by bedding materials or other absorbents (Fig. 90). According to Heck (1931), when all the solid and liquid excrements from a cow are mixed with sufficient straw to absorb the

liquid, the manure obtained will contain from 10 to 12 pounds of nitrogen to a ton. If the manure is allowed to stand a few days, about half the nitrogen will be present in the form of ammonia.

Straw reduces solubility of manure nitrogen. Straw, peat, moss, or other cellulose-rich material constitutes an important part of manure, as it absorbs the liquid excretion, and on decomposition,

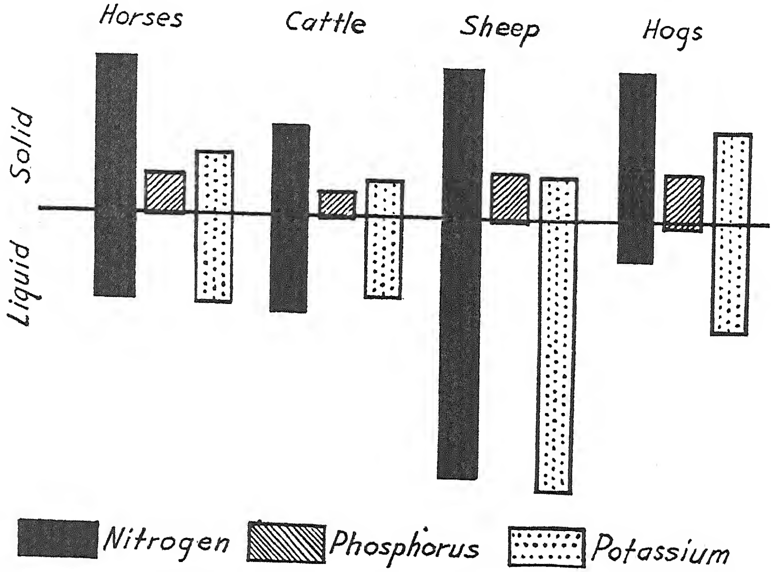

Fig. 90. Comparative quantities of fertilizing elements contained in the solid and liquid excrements of farm animals. (After Duley.)

adds fertilizing substances to the manure. Straw is most commonly used for bedding. It proves to be a good absorbent; and as a source of energy, it favors biological fixation of ammonia. Much coarse litter or undecomposed cellulose-rich material may greatly reduce the fertilizing value of manure, since it provides energy for soil bacteria and fungi (Ch. 5).

Conservation of manure. Under the best of conditions, there is an unavoidable loss of about 15 percent of the total nitrogen eliminated by animals, resulting from volatilization and from activity of micro-organisms. This loss varies according to the quantity of water present. Considerable quantities of nitrogen may be lost from sheep and horse manures, owing to their being dryer and

hence more concentrated than those produced in the care of cows and hogs.

Usually manures are not used immediately after they are made; this fact necessitates keeping them until a time when they can be conveniently used. During the time manure is kept and until it is incorporated into soils, it suffers mechanical losses and losses through leaching and volatilization, and it undergoes chemical changes (largely oxidation) brought about by the activities of bacteria and fungi that flourish in it. These chemical changes result in losses of both organic matter and nitrogen.

As much as 40 percent or more of the soluble materials may be lost when manures are made in open yards and when they are thrown into loose heaps and left exposed to the weather. The least losses occur when manures are tightly packed and when, at the same time, they contain as much water as they can hold without drainage, under which conditions they may be stored in open "pits" or other favorable places for long periods without much loss of nitrogen.

Feeding sheds. When cattle or sheep are fattened in covered yards, the manure should be left under the animals until it is needed. If the animals are fed in the open, the manure should be hauled out and "clamped"—that is, stored in a compact pile with nearly vertical sides and a flat top. When thus piled, it should be kept sufficiently moist to prevent "fire-fanging" or burning, but not so wet as to cause dark-colored liquid to drain from it. Stall manure may be conserved in a similar manner.

Storage of liquid manure. When necessary, liquid manures can best be stored in closed tanks or cisterns, according to the common practice of European farmers. Owing to the fact that the nitrogen in stored liquid manure is mostly in the form of ammonium carbonate, it may be easily lost (as ammonia) through volatilization. Danish investigators have found that this loss can be completely eliminated by making the cisterns air-tight. German investigators have demonstrated that the losses from volatilization can be lessened materially by covering the surface of the liquid with a layer of mineral oil.

Fresh v. composted manure. Fresh manure, especially if it contains much straw or other cellulose-rich materials, is not so valuable a fertilizer as that which has undergone partial decomposition,

as in composting. Experienced gardeners and truck growers know the advantages in using composted manures.

Whether in compost heaps or in soils, manure undergoes important changes that affect the nitrogen and celluloses. If the manure is rich in urea and water-soluble nitrogen compounds, ammonia is formed, some of which volatilizes and some of which is assimilated by micro-organisms. During the production of this ammonia, decomposition of the celluloses is delayed, probably because of a temporary alkaline reaction, or increase in pH value. Then follows decomposition of the celluloses and complex insoluble nitrogen compounds, with a decrease in pH values.

In the decomposition of celluloses, the micro-organisms concerned require nitrogen as ammonia and amides, formed in decomposition of nitrogenous matter. Nitrogen assimilated by the organisms is fixed in their cells, thus decreasing the quantity of available nitrogen. It is better that these changes be allowed to take place in a compost heap than in soils, as an application of much fresh, strawy manure may cause a depression of soil nitrates. Manure formed when shavings and sawdust are used for bedding compares favorably with that made when straw is used.

Availability of manure nitrogen. Ordinarily, about half the nitrogen in fresh manure becomes available to crops the first year. The source of this nitrogen is the liquid excrement. According to Heck (1931), as much as 80 percent of the urea nitrogen may be used by crops the first year if fresh manure is turned under immediately after application. More nitrogen is rendered available the first year when manure is applied as top-dressing and disked in than when it is plowed under.

Applying manure. On the heavier-textured soils like silt loams and clay loams, it is best to plow under fresh manure in the fall, during winter (if possible), or in early spring, for the following reasons: it helps to loosen the soil materials; it favors better drainage; it facilitates frost action; and it leads to assimilation and hence conservation of soluble nitrogen by micro-organisms. Manure may also be used to top-dress wheat, hay crops, and pastures.

For sandy soils, composted manures are best, but they should be applied as top-dressing and disked in.

In the United States, manure is used mostly for Indian corn. Other crops that receive manure are hay, wheat, potatoes, and

tobacco. In some sections, as in New England and New York, hay receives most of the manure. In the Middle West practically all manure is used for maize.

Liquid manure, which is especially rich in nitrogen and potassium, may best be used on fields in grass and hay, although it may also be used for other crops. When thus used, it should be incorporated into the soils at once.

Experiments have shown that when the manure supply is limited, it is more profitable to cover as many acres as possible at the rate of 6 or 8 tons per acre than to make heavier applications on less acreage. In general farming, it is a good practice to mix horse and cow manures. The one is comparatively dry and warm, whereas the other is commonly regarded as wet and cold. Mixing the two aids conservation of fertilizing elements, and facilitates handling.

Manure may be hauled directly to the field, or it may be piled for a time, and then hauled out. When brought to the field, it may be immediately incorporated into the soil, or it may be left exposed in small piles or scattered upon the ground. In either case, less loss of nitrogen occurs when manure is immediately turned under or disked in. When left exposed, fresh manure suffers less loss on drying than composted manure, because of the fact that in fermentation the urea nitrogen is converted into ammonium carbonate and organic acids which will volatilize when manure that is moist and partly composted is left exposed and dries out. Accordingly, fresh manure that is left in small piles in fields and dries out loses more nitrogen than when it is scattered at once (Fig. 91).

Residual effects of manure. The effects of farmyard manure on soils, especially on the heavier types, persist over several years. In general, about half the nitrogen in manure is rendered available during the first year, and about one fourth of the phosphorus and potassium is used.

Reinforcing manure with phosphate. Thorne (1907) and other investigators have found that when manure is reinforced with from 25 to 40 pounds of superphosphate or from 40 to 80 pounds of rock phosphate per ton, its fertilizing efficiency is greatly increased, especially on soils that are deficient in available phosphorus.

Manure v. chemical fertilizers. Although chemical fertilizers may, for a few years, give higher comparable yields than farmyard manure, long-time fertilizer tests have shown that the superiority of the chemical salts is only temporary. Continued use of some chemical fertilizers may so change the nature of soils as to result in infertility (Fig. 92). When used alone, manures may prove to be more effective in maintaining soil fertility, and with less seasonal fluctuation in yields, than chemical fertilizers. On the

Fig. 91. Applying farm manure by means of a manure spreader.

other hand, stall manures may be regarded as dangerous carriers of troublesome livestock parasites.

On crop plants like clover, citrous and deciduous fruit trees, and gooseberries, manure produces favorable results that cannot be effected by chemical fertilizers. In addition to favorably affecting soil aëration and tilth, farm manures supply crop plants with fertilizing elements, replenish the soil supply of organic matter and humus, afford good sources of carbon dioxide for plants, produce beneficial effects on the helpful soil micro-organisms, and supply crops with certain trace essentials which are not ordinarily present in chemical fertilizers.

Artificial farm manures. Composting straw, leaves, and refuse materials, as well as farmyard manures, is a very old practice in

preparing organic fertilizing materials. The value of such composts is determined by the kind of material used and stage and character of decomposition.

Hutchinson and Richards (Eng., 1921) have developed a process for producing artificial farm manures by treating alternate layers

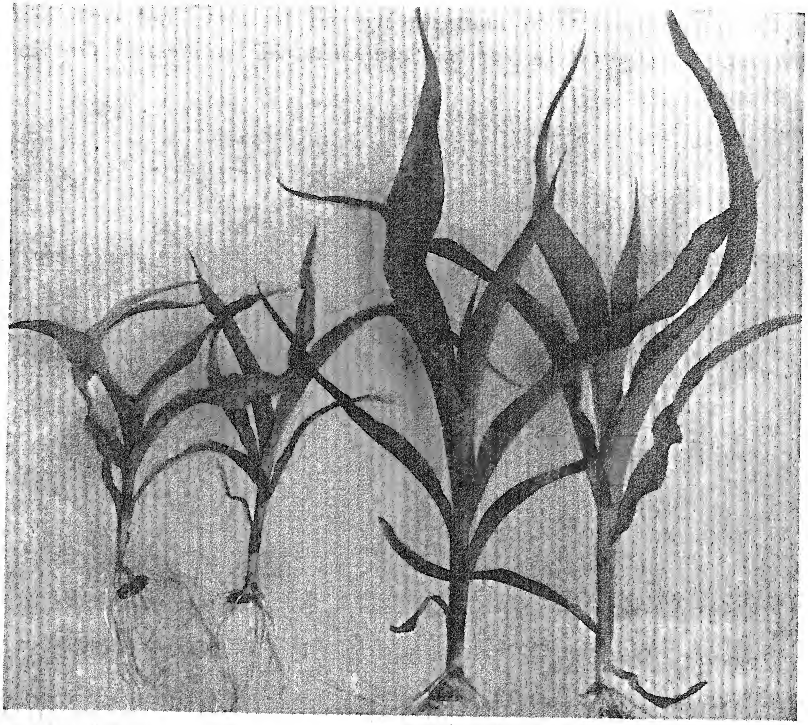

Fig. 92. Acid-forming chemical fertilizer may decrease soil fertility. Left—Maize plants resulting from continual use of sulphate of ammonia on acid soil (pH 4.5). Right—Comparable plants resulting when agricultural lime was used in conjunction with sulphate of ammonia, but not mixed together.

of straw with sulphate of ammonia and pulverized limestone, and by adding sufficient water to effect quick and thorough decomposition of the straw. The process has been improved by including phosphate in the materials added, and it has been patented.

Several investigators have demonstrated that good grades of manure can be produced by composting such materials as straw and corn stalks with certain chemicals, provided the compost heap

is kept sufficiently moist to prevent loss of nitrogen. Inoculating the composts with fresh stall manure, soil material, or cultures of molds (fungi) may accelerate decomposition.

According to Albrecht (1936), straw, corn stalks, cotton hulls, and other farm organic residues may be readily composted by adding 67.5 pounds of sulphate of ammonia, 60 pounds of finely pulverized limestone, and 22.5 pounds of superphosphate per ton of dry matter. When piled about 6 feet high with flat top for allowing intake of rain water, decomposition takes place as the moisture allows. The compost heaps and application of the nutrient materials may be done by hand or through mechanical means.

Green manures and fertilizing values. The subject of green-manuring has been treated in Chapter 18. However, a word will be given here regarding comparative fertilizing values of green manures, as based on available nitrogen and soluble humus. White (1930) has conducted laboratory experiments in which he incorporated green crop residues into soil materials at a rate equivalent to 20 tons of dry matter per acre, with the following results:

COMPARATIVE FERTILIZING VALUES OF GREEN MANURES
(Period of Experiment, 9 Months)

Source of Green Manure	Nitric Nitrogen (N) Found per Acre (Av. for 8 mo.)	Soluble "Humus" per Acre	Source of Green Manure	Nitric Nitrogen (N) Found per Acre (Av. for 8 mo.)	Soluble "Humus" per Acre
	Pounds	*Pounds*		*Pounds*	*Pounds*
Red clover...	84*	7,600	Rape......	119	400
Alfalfa......	73	7,200	Wheat.....	114	11,600
Sweetclover..	65	1,800	Maize......	67	2,400
Peas (Canada)	63	2,400	Oats.......	55	3,200
Soybeans....	60	1,400	Rye.......	10	3,600
Hairy vetch.	48	3,400	Timothy...	—16	5,000

* All quantities are expressed in pounds per acre in excess of untreated soil material.

Guanos like those that are obtained from small, dry islands off Peru and South Africa consist principally of excrements of sea birds (guanayes). The content of fertilizing constituents of these organic fertilizers varies considerably. Some contain as much as 14 percent nitrogen (N), whereas others (phosphatic) analyze as high as nearly 14 percent phosphorus (P) and 5 percent potassium (K). Ordinary Peruvian guano contains from 5 to 8 percent nitrogen, from 6 to 7.8 percent phosphorus, and from 1.5 to 3.3 percent potassium. Inasmuch as the food of guanayes consists

entirely of fish, production of guanos may be regarded as a process of recovering fertilizing elements from the sea.

There are also bat guanos which are found in caves.

The successful introduction of Peruvian guano as fertilizer during the early 1840's and the manufacture of superphosphate by Lawes (Eng.) in 1843 mark the beginning of a new era in agriculture.

Sewage sludge. The fertilizing value of sludge that is produced in municipal sewage disposal varies widely, owing to different purifying processes. Considerable sewage is produced by sedimentation and digestion in Imhoff tanks, followed by draining on cinder or sand beds. Moist sludge thus produced contains about as much nitrogen as farmyard manure. The best of these organic fertilizing materials are the so-called "activated sludges" which are produced by forcing air through the sewage. These organic materials, which contain from 5 to 6½ percent nitrogen and from less than 1 to about 1.7 percent phosphorus, may be used as fertilizers. They also contain traces of copper, zinc, manganese, and boron.

Other organic fertilizers. Almost any material of plant or animal origin may be used for fertilizing plants. If such materials can be prepared to contain more than 5 percent nitrogen, they may become articles of commerce. Some organic fertilizing materials (water-insoluble) are listed in the following table:

WATER-INSOLUBLE SOURCES OF NITROGEN

MATERIAL	NITROGEN * (N)	PHOSPHORUS		POTASSIUM	
		Element (P)	Equivalent as P_2O_5	Element (K)	Equivalent as K_2O
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Blood meal or dried blood	6–14	0.9–1.7	2–4	—	—
Fish guano (scrap)	7–10	2–3.9	4.5–9	0.8	1.0
Cottonseed meal	6–7	0.9–1.3	2–3	1.2–1.7	1.5–2
Tankage	5–10	3–6.5	6.8–15	—	—
Meat meal	10–14	2–3	4.6–7	—	—
Meat meal (bone added)	5–6	5–7	11.5–16	—	—
Oil cakes	5.0	0.9	2.0	0.8	1.0
Shoddy	5–12	—	—	—	—
Garbage tankage	2.5–3.3	0.6–2.2	2–5	0.4–1.2	0.5–1.5

* Nitrogen in protein forms.

NITROGEN FERTILIZERS (WATER SOLUBLE)

The water-soluble carriers of nitrogen may be grouped into four classes, as follows: (1) nitrates that contain nitric nitrogen (NO_3),

like nitrate of soda ($NaNO_3$) and calcium nitrate, $Ca(NO_3)_2$; (2) ammonium salts that contain ammonic nitrogen, like ammonium sulphate, $(NH_4)_2SO_4$; (3) compounds that contain both nitric and ammonic nitrogen, like ammonium nitrate (NH_4NO_3); and (4) compounds that contain other forms of nitrogen, and that give rise to ammonium ions on decomposition, like Cyanamid ($CaCN_2$) and urea, $CO(NH_2)_2$.

Until the World War (1914-1918), the principal nitrogen fertilizers were natural nitrate of soda and by-product sulphate of

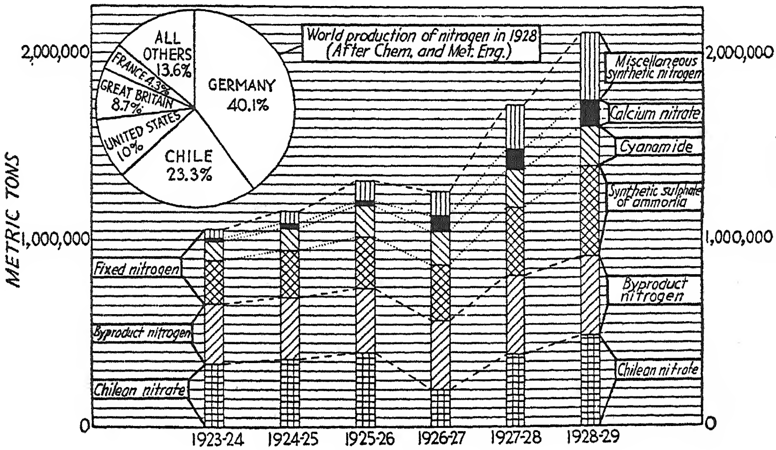

Fig. 93. World production of nitrogen (N), in metric tons of 2,204.6 pounds, for years ending May 31. (After statistics of the British Sulphate of Ammonia Federation, Ltd.)

ammonia. Although for 12 years prior to the war chemical fixation of atmospheric nitrogen on a limited commercial scale was an established fact (Ch. 9), synthetic nitrogen fertilizers were not made in appreciable quantities until after 1913. During the war extensive nitrogen-fixation factories were erected in Central Europe for the production of ammonia and nitrates. Since the war, other countries have erected nitrogen-fixation plants with a view to becoming self-sufficient in nitrogen. The extensive development of the nitrogen-fixation industry has resulted in an enormous increase in the world production of nitrogen fertilizers (Fig. 93).

Fixation of atmospheric nitrogen. Chemical fixation of atmospheric nitrogen consists in combining nitrogen with other elements to render it available for commercial use. This may be accom-

plished by the electric-arc, cyanamide, and synthetic-ammonia processes.

Electrical nitrogen fixation occurs in nature during lightning flashes. Here the products consist of ozone of the lower atmosphere, ammonia, and oxides of nitrogen. Of the total quantity of nitrogen fixed in nature, electrical discharges are responsible for about 5 percent. In some places the quantity thus fixed may amount to 10 or more pounds of nitrogen per acre annually.

The arc process consists essentially in partial conversion of nitrogen and oxygen, at high temperature, into nitric oxide (NO) by passing air rapidly through a zone of exceedingly high temperature produced in an electric-arc furnace. The nitric oxide produced, on cooling in the presence of accompanying oxygen, forms nitrogen dioxide (NO_2) which, in turn, forms dilute nitric acid when it is absorbed in water.

As early as 1785, Cavendish (Eng.) discovered that nitrogen unites with oxygen when electric sparks are passed through a mixture of the two gases; but no technical or commercial use was made of this discovery for more than 100 years—not until 1902, when Bradley and Lovejoy built the first nitrogen-fixation factory in the world at Niagara Falls, N. Y. The particular process used here (arc) was not in use after 1904, owing to the appearance of more efficient processes.

Birkeland and Eyde completed their arc-process nitrogen-fixation factory at Notodden, Norway, in 1905. With the exception of 4,500 tons of nitrogen in Germany and about 1,250 tons in France (1929), the fixation of air nitrogen by the arc process has been confined to Norway. The Norway products are calcium nitrate, sodium nitrate, sodium nitrite, and nitric acid.

The cyanamide process consists in bringing atmospheric nitrogen in contact with finely pulverized calcium carbide (CaC_2) heated to 1,000° C. This results in the formation of calcium cyanamide (cī-ăn-ăm′īde, $CaCN_2$) whose fertilizer trade name in America is Cyanamid (cī-ăn′ȧ-mĭd). The calcium carbide is prepared by fusing a mixture of lime (CaO) and coke (C) by means of a powerful electric current in the absence of air. The nitrogen is obtained by separating it from the atmosphere by liquefying and distilling air.

Calcium cyanamide was first produced from commercially impure carbide by Frank and Caro (Ger.) in 1895. When it was

found (1901) that this compound might be used directly as a fertilizer, the process of its production underwent rapid development. The process was first installed commercially in Italy (1905) and soon thereafter in Germany. A plant erected at Niagara Falls, Ontario, began making Cyanamid in December, 1909. Such plants have been established in 13 different countries, including 41 factories with a total annual capacity, in 1929, of more than 460,000 tons of nitrogen. During the year ending May 31, 1930, more than 260,000 tons of atmospheric nitrogen were fixed as calcium cyanamide. This product is used mainly as fertilizer, but a considerable quantity is converted into various chemicals for industrial and agricultural uses. Improvements in this process by French and German chemists indicate the possibility of producing calcium cyanamide without the intermediate production of calcium carbide.

The direct synthetic-ammonia process accomplishes direct synthesis of ammonia (NH_3) by passing a compressed mixture of 1 volume of pure nitrogen and 3 of pure hydrogen over a catalyst (such as iron oxide) at high temperature. This process is not dependent on cheap electric power as are the arc and cyanamide processes. A number of methods of operation have been developed, including the Haber-Bosch (Ger.), Fauser (It.), Claude (Fr.), Casale (It.), and American, in all of which nitrogen is fixed with hydrogen in the presence of a catalyst. Nitrogen may be obtained by separating it from the oxygen of the atmosphere either by liquefaction and distillation or by burning the oxygen out with hydrogen. The hydrogen may be obtained from water by electrolytic decomposition, from water gas, coke-oven gas, or as a by-product of coking.

The direct synthetic-ammonia process, which is the most modern, was developed by Haber and Bosch, who had put into operation a pilot plant at Oppau, Germany, in 1913. In 1928, 40.1 percent of all the commercial nitrogen produced in the world was fixed in Germany (Fig. 93). As its name indicates, the direct product of this process is ammonia gas. This gas is used in the production of nitrogen fertilizers, mixed and concentrated fertilizers, nitric acid, various chemicals for industrial and agricultural uses, and nitrogen and hydrogen by cracking anhydrous ammonia; it is also used for refrigeration and various other purposes. Seventy-five synthetic-ammonia factories have been erected in 17 countries, with

a total annual capacity of more than 1,700,000 tons of nitrogen (N), as of the calendar year 1929.

Shift in world nitrogen dependence. The significance of the change in dependence of the countries of the world on natural nitrate and by-product ammonia to fixed-nitrogen products for nitrogen is profound. The chemical processes for fixing air nitrogen have been perfected to the extent that there will always be a supply of nitrogen for agriculture the world over. Natural nitrate and by-product ammonia have their limits, but the free nitrogen of the atmosphere is unlimited. The earth's atmosphere actually contains millions of millions of tons of nitrogen. It has been estimated that the air over each square mile of the earth's surface contains as much as 20,000,000 tons of elemental nitrogen.

By-product nitrogen. In coking, the nitrogen contained in coal becomes distributed between the different products formed—coke, tar, and gases. The gases constitute the only valuable source of by-product nitrogen. The nitrogen is present as ammonia. This ammonia is recovered by washing the gases with water or sulphuric acid, which results in the formation of ammonium sulphate (Fig. 93).

Nitrogen fertilizers. The following are the principal fertilizing salts that carry nitrogen only:

Name	Nitrogen Percent	Name	Nitrogen Percent
Nitrate of soda	15½-16	Calnitro, Nitrochalk, etc.	15½-20½
Calcium nitrate	15½	Leunasalpeter	25½-26
Sulphate of ammonia	20-21	Cyanamid, Nitrolim, etc.	22
Ammonium chloride	26	Urea (Floranid)	46
Ammonium nitrate	35	Calurea	34

Nitrate of soda ($NaNO_3$) is obtained from natural deposits in the rainless areas of northern Chile and is also manufactured as a fixed-nitrogen product (Fig. 94). Natural nitrate of soda contains valuable trace elements like iodine and boron, and is one of the oldest nitrogen fertilizers. Although the first shipment of natural nitrate was from Iquique (then Peru) in 1830, its consumption did not increase materially until 1880, for which year the total world consumption amounted to 223,800 short tons.

All the nitrogen in nitrate of soda is in the nitric or nitrate form (NO_3). Aside from its general use, this fertilizer is particularly suitable for use in emergency cases—when plants are suffer-

ing from pest or disease attacks, to meet depression of soil nitrates, and to supply available nitrogen during cold weather. It is also particularly suitable for side-dressing (application along the row after the crop is up) and top-dressing (broadcast over the surface, as on pastures).

Calcium nitrate, or nitrate of lime, $Ca(NO_3)_2$, is made synthetically in Germany and Norway (Fig. 93). It contains about 14½

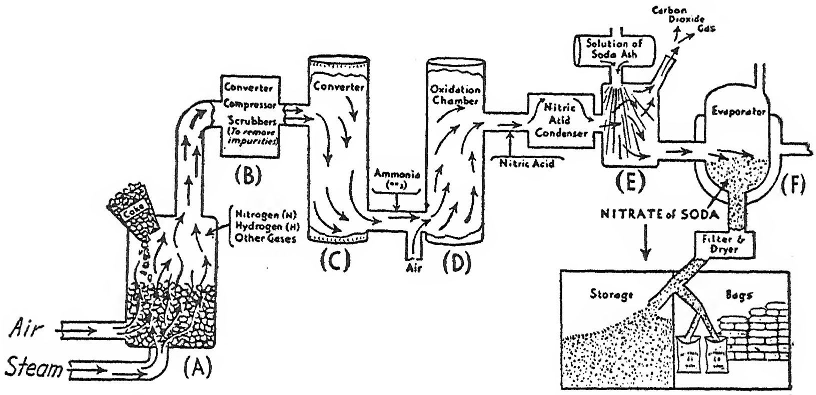

Fig. 94. Principal steps in the processes for the fixation of atmospheric nitrogen as nitrate of soda. A, The first step. Air, containing the nitrogen, and steam are blown through glowing coke, producing a number of gases, including nitrogen and hydrogen. B, Converter and compressor, and "scrubbers" to remove impurities from the nitrogen and hydrogen gases. C, Converter in which the nitrogen and hydrogen are combined under pressure and heat, forming ammonia. D, Chamber in which the ammonia is burned with air (oxidized), forming nitric acid. E, Mixer in which nitric acid reacts with soda ash (solution) and forms nitrate of soda.

percent nitrate nitrogen and about 1 percent ammonic nitrogen. This fertilizer is very deliquescent and very soluble. It is used for fertilizing pasture grasses, wheat, oats, hay, barley, forage crops, sugar beets, cabbages, and mangels. It is particularly good for acid soils, and it may be used in emergency cases and as side-dressing and top-dressing. This form of nitrogen may be compared favorably with that of nitrate of soda and potassium nitrate.

Sulphate of ammonia, $(NH_4)_2SO_4$, was formerly made entirely from by-product nitrogen; but since the development of nitrogen-fixation processes, synthetic sulphate of ammonia has become one of the principal nitrogen fertilizers. For the year ending May 31, 1929, the quantity of nitrogen used in the production of synthetic

sulphate of ammonia was practically equal in tonnage to that contained in the total quantity of Chilean nitrate produced during the same period (Fig. 93).

The use of ammonium salts as fertilizer was developed in England, owing to the early experimental work of Lawes and Gilbert. It has been the principal source of nitrogen in many mixed fertilizers, and may be used singly for practically all crops. The ammonic form of nitrogen is not so easily leached from soil materials or from bare soils as is nitric nitrogen, because, being basic, it can temporarily displace hydrogen and other cations in soil base-exchange compounds (Ch. 4). In soils, this fertilizer is acid-forming.

Sulphate of ammonia has always contained sufficient free acid (about 0.05 percent) to give it a strongly acid reaction, to cause rotting of bags, and to effect unfavorable physical condition of the fertilizer itself. Improved processes developed by Fauser (It.) turn out dry and "neutral" sulphate that contains a slightly higher percentage of nitrogen.

Ammonium chloride, (NH_4Cl), with its 26 percent nitrogen, has not found favor in the United States. In Germany, however, it is produced on a large scale from synthetic ammonia. Like sulphate of ammonia, it increases soil acidity or lowers pH values.

Ammonium nitrate (NH_4NO_3) is a fixed-nitrogen product, being one of the first synthetic fertilizers made. Half its nitrogen is in the ammonia form, while the other half is in the nitrate form. It is more than twice as soluble as nitrate of soda, and it leaves no residue in soils. Because of its tendency to attract moisture, this fertilizer is difficult to handle. In general, it has given good results on farm crops, acting very much like nitrate of soda.

Calnitro (Ger.), Nitrochalk (Eng.), and calcium carbonate-ammonium nitrate (Am.) are mixtures of ammonium nitrate and calcium carbonate. The German product contains 20½ percent nitrogen; the American, 18 percent; and the English product, 15½ percent. A similar French product, called "Ammonitre," contains gypsum instead of carbonate, and contains 15½ percent nitrogen. These products each contain equal quantities of ammonic and nitric nitrogen.

Leunasalpeter, $(NH_4)_2SO_4 \cdot NH_4NO_3$, is a German synthetic fertilizer, consisting of a double salt of ammonium sulphate and ammonium nitrate. Its 26 percent nitrogen includes 19½ percent

ammonic and 6½ percent nitric nitrogen. It is less hygroscopic than ammonium nitrate, but more so than ammonium sulphate. A similar French product, called "le sulfonitrate d'ammoniaque," contains 25½ percent nitrogen. In soils, its acid-forming properties are about two thirds that of sulphate of ammonia.

Cyanamid and Nitrolim (calcium cyanamide + lime, $CaCN_2$ + CaO) contain 22 percent nitrogen and 40½ percent calcium. All the nitrogen is in the cyanamide (CN_2), hence chemical organic, form. About one third of the calcium is in the form of free lime (CaO) and the remainder is in combination as cyanamide. When applied to soils, the cyanamide nitrogen, owing to some chemical agent, becomes urea, or carbamide, $CO(NH_2)_2$, which, in turn, is converted into ammonium carbonate; then it is oxidized to nitrate. The calcium residue affects soils beneficially, particularly if they are acid.

If it is not well distributed or mixed with soil material, calcium cyanamide forms dicyanodiamide which is toxic to plants and nitrifying bacteria. On the heavier soils, disappearance of the cyanamide is usually rapid, with but little toxic substance formed; but on sandy soils, the disappearance is slow. For best results, this fertilizer should be applied from 7 to 20 days before planting. In England its use is restricted to spring-sown crops. It should be thoroughly mixed into soils; and when stored, it should be kept in a dry place to prevent formation of dicyanodiamide. It is not advisable to use old material.

Urea (Floranid), $CO(NH_2)_2$, is prepared synthetically by combining ammonia and carbon dioxide gas under suitable conditions. It can be produced directly from ammonia and calcium cyanamide. With a nitrogen content of 46 percent, it is the most concentrated nitrogen fertilizer. Its nitrogen is in the amide, hence chemical organic, form (NH_2). In soils urea is converted into ammonium carbonate, which, in turn, is nitrified. It has proved to be a good source of fertilizer nitrogen. Its first effect on soils is basic, owing to the formation of ammonium carbonate. Its residual effect, however, is acidic. Its attraction for moisture has greatly restricted its use as such. Urea also appears on the market in the form of urea-ammonia liquor.

Calurea is formed by chemically combining calcium nitrate and urea in solution. It contains 34 percent nitrogen, of which one

fifth is in the nitrate form (NO_3) and four fifths in the amide form (NH_2), which is ammonia with an atom of hydrogen removed.

Nitric v. ammonic nitrogen for plants. According to their chemical nature, nitric (NO_3) and ammonic (NH_4) nitrogen are opposite forms of this element; the one is acidic, whereas the other is basic. This does not necessarily mean that plants will absorb one or the other according to the form in which nitrogen occurs in fertilizers that may be used. We find, on the contrary, that fertilizer nitrogen other than the nitric form may be entirely converted into nitrates when incorporated into soils. Inasmuch as nitrification is a natural process, it would seem that plants require only nitrate nitrogen, according to the natural order of things. So thought the earlier investigators. But it is now generally recognized that higher plants can absorb and assimilate ammonium nitrogen also.

Results of inquiry into plant nutrition indicate clearly that most crop plants can absorb and assimilate both forms of nitrogen. Some crops seem to indicate favorable responses to ammonium nitrogen under field conditions. In culture mediums maintained at neutral and slightly acid reactions, buckwheat, oats, cotton, soybeans, and maize have been found to grow best with ammonic nitrogen during the first part of the growing period, and with nitric nitrogen during the remainder of the period of vegetable growth. Absorption of ammonium nitrogen is more important in the growth of buckwheat than of oats. Other plants such as sugar beets, barley, and sweetpotatoes seem to "prefer" nitrate nitrogen during all stages of growth. It would seem, therefore, that the nitric form of nitrogen is essential for later stages of growth or for maturity (Fig. 95).

Inasmuch as the nitrogen in plant proteins is in the amine form (NH_2), it would seem that in protein synthesis green plants would require ammonic nitrogen. According to Kostychev (Russ., 1931) and Maximov (Russ., 1930), when ammonium salts are used in plant nutrition in proper culture mediums, the absorbed ammonic nitrogen is changed in the roots to substances like asparagine and glutamine which are carried in the organic (amino) compounds to the leaves (Ch. 9). On the other hand, when nitric nitrogen is absorbed, it may be carried to the leaves as such, and there it must undergo reduction to the amine form. The conversion of nitrate nitrogen to simple amino compounds is accomplished by means of

a substance known as *reducase.* Reduction of nitrate nitrogen parallels the reduction of carbon dioxide. But as absorption of ammonic nitrogen easily interferes with the nutrition of plants, nitric nitrogen seems to be the better form for most plants, as indicated by soil nitrification and plant nutrition under natural conditions.

Prianishnikov (Russ., 1923, 1929) and other investigators have observed that under proper conditions, ammonium nitrogen may

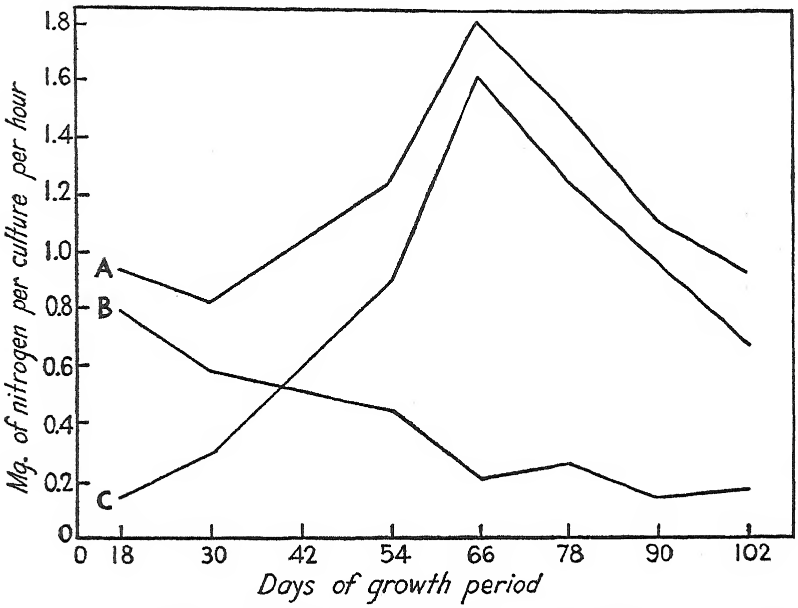

Fig. 95. Quantity of nitrogen absorbed during growth of oat plants which were grown in culture solutions containing equal proportions of NO_3 and NH_4: A, total nitrogen; B, ammonium nitrogen (NH_4); C, nitrate nitrogen (NO_3). (After Stahl and Shive.)

be absorbed faster and assimilated more freely (by some plants) than nitrate nitrogen, but that injury may result more easily from excess of ammonic than of nitric nitrogen, owing in part to development of acidity in the culture mediums by ammonium salts. Other factors may be acidity of cell sap and quantity of carbohydrates in the plants. So long as the acidity of the mediums and concentration of ammonic nitrogen are regulated, ammonium salts may be regarded as excellent fertilizing materials. Prianishnikov

has suggested that probably nitrification in soils may serve to regulate the accumulation of ammonia.

The work of several investigators in different countries shows that ammonic nitrogen, within certain limits of concentration, is not toxic to green plants when growing in neutral or slightly acid mediums or in the presence of adequate calcium and magnesium. According to McKee (Eng., 1937), the intake of ammonium ions depends on available carbohydrates within the plants.

Results of these investigations seem to indicate four things: (1) the advisability of including some ammonium compounds in fertilizer mixtures for crop plants that give optimum growth with ammonic nitrogen during early stages; (2) preferred use of nitrate fertilizers on medium-acid and strongly acid soils; (3) efficient use on neutral and slightly acid soils of ammonium salts and other compounds which, on decomposition, give rise to ammonia; and (4) the need of crop plants for nitrate nitrogen during later stages of vegetable growth.

Ammonia as fertilizer. In western United States, on alkaline soils, it has been shown that crops can be profitably fertilized with nitrogen through the use of gaseous ammonia, which is forced into irrigation water while it is being applied.

Leaching of ammonic v. nitric nitrogen. According to leaching experiments with soil materials in laboratories and on bare soils and soil materials outdoors, nitrate nitrogen is readily leached, especially from sandy soils and soil materials. Leaching results show that practically all the nitrogen in drainage waters is in the nitrate form, indicating that when forms of nitrogen other than nitrate are applied, the nitrogen is converted into the nitric form before it leaches. Leaching data also show that soil materials have stronger retaining power for ammonium (NH_4^+) than for nitrate ions (NO_3^-). Thus it would seem that excessive losses of nitrogen will occur when nitrates are used for fertilizing crops, but this is not necessarily the case. Heavy losses may occur, however, when much rain follows applications of nitrate on sandy soils.

Leaching studies made under normal conditions and on cropped soils and soil materials show that not all the fertilizer nitrogen, whether applied as nitrate or in other forms, is utilized by crops; some of it is never recovered. The greatest loss commonly occurs through leaching. Some nitrogen presumably escapes in gaseous

form. Some of the applied nitrogen remains in the soils in the roots of plants and in the bodies of micro-organisms.

Recovery of nitrogen by crops. In recovery-of-nitrogen experiments conducted in England, Germany, and the United States, including the use of sulphate of ammonia and nitrate of soda for 8 different crops, average comparable results show that, ordinarily, crops recover about 50 percent of the nitrogen added in these two fertilizers. The percentage recovery varied from 18 to 28 percent for rutabagas, potatoes, oats, and timothy to as much as from 60 to 90 percent for sugar beets, mangels, wheat, and potatoes. Average results also show that about 12 percent less nitrogen was recovered from sulphate of ammonia than from nitrate of soda.

Results of experiments indicate that soil reaction may be an important factor affecting nitrogen recovery. Acidity and absence of adequate calcium and magnesium may cause crops to utilize more nitrogen from nitrates than from ammonium sources. From long-time plot experiments, Lipman and Blair (1918, 1929) found that without lime less nitrogen was recovered by crops that had received ammonium nitrogen than by those that had received nitrate of soda; whereas when lime was used, less nitrogen was recovered in crops that received the nitrate. The New Jersey field experiments with maize, oats, wheat, and timothy show greater recovery of nitrogen from nitrate of soda than from sulphate of ammonia on unlimed plots, less recovery from nitrate of soda than from sulphate of ammonia on limed plots, less recovery from nitrate of soda on limed than on unlimed plots, and greater recovery from sulphate of ammonia on limed than on unlimed plots.[1] In the cylinder experiments, lime increased the recovery of nitrogen from both nitrate of soda and sulphate of ammonia, with a 15-percent higher average recovery from the nitrate.[2]

Nitrate v. ammonium salts on soil nitrogen. It does not follow that, because basic ammonium ions are absorbed by base-exchange compounds, a soil will accumulate more nitrogen when crops are fertilized with ammoniacal than with nitrate forms of nitrogen. On nonacid soils but little difference in nitrogen may result, as is indicated by the soil content of carbon and nitrogen of the Broad-

1 LIPMAN, J. G., and BLAIR, A. W. FIELD EXPERIMENTS ON THE AVAILABILITY OF NITROGENOUS FERTILIZERS, 1908-1917. *Soil Science,* Vol. 9, No. 5, p. 384. 1920.

2 LIPMAN, J. G., BLAIR, A. W., and PRINCE, A. L. INVESTIGATIONS RELATIVE TO THE USE OF NITROGENOUS PLANT-FOODS, 1913-1927. N. J. Agr. Expt. Sta. Bull. 519, p. 18. 1931.

balk wheat plots at Rothamsted, after from 63 to 71 years of cropping:

EFFECTS OF NITRIC AND AMMONIC FORMS OF NITROGEN ON SOIL CONTENT OF CARBON AND NITROGEN

Soil Treatment	Quantity of Nitrogen Added per Acre Annually	Content of Carbon 1914	Content of Nitrogen 1914
	Pounds	*Percent*	*Percent*
No nitrogen applied	none	0.15	0.104
Nitrate since 1852	43	1.52	0.116
Ammonium salts since 1844	43	1.14	0.111

Residual fertilizing effects of nitrogen fertilizers. Owing to the fact that, under normal conditions, the nitrogen reserve of a soil is determined by its content of organic matter, nitrogen of chemical fertilizers cannot be retained long by soils, except as it is fixed in complex, insoluble, organic compounds. Residual fertilizing effects of nitrogen fertilizers may result from increased quantity of crop residues like roots and stubble, temporarily retained nitrogen, and, in case of grasses and legumes such as alfalfa, from increased root reserves. Conditions for residual-nitrogen effects may obtain in orchards. Surr (1927) has reported results of experiments in which fertilizers were applied annually to orange trees for 5 successive years (1915-1919), and discontinued thereafter. All plots were then treated with a uniform application of peat. In 1923, the following results were obtained:

RESIDUAL EFFECTS OF FERTILIZER NITROGEN ON ORANGES AT RIVERSIDE, CALIFORNIA
(Fourth Year After Fertilizers Were Discontinued)

Previous Treatment	Yield of Oranges per Tree
	Pounds
No fertilizer	5
Ammonium nitrogen, as sulphate	130
Nitrate nitrogen, as nitrate of soda	154

The comparable yields show that the residual fertilizing effects of nitrate of soda on orange trees were 18 percent greater than from sulphate of ammonia.

Ordinarily, fertilizer nitrogen is applied in comparatively small quantities to assist crop plants during early growth and for imme-

diate use in emergency cases, and in larger quantities annually to meet current needs of the crops.

Relative efficiency of nitrogen fertilizers. For a given crop, data on which relative "efficiency" of nitrogen fertilizers may be determined are usually obtained by applying equal quantities of nitrogen per acre, other conditions being equal. The increase from nitrate of soda has commonly been used as a base relative, and the relative values of the others are obtained by dividing the increase from each by the increase from the fertilizer selected as the standard. For example, the acre increases from three nitrogen fertilizers—A, B, and C—are 20, 18, and 16 bushels of wheat, respectively. Relatively, the increase from A (20 bu.) is regarded as 100; that from B, as 90 (90 percent of 20); and that from C, as 80.

Inasmuch as several factors affect the action of a nitrogen fertilizer—including soil temperature, moisture, soil reaction, leaching, time and method of application, and kind of crop—relative fertilizer values obtained in the manner just described have little or no scientific value, and, practically, may be misleading.

It would seem that knowledge regarding time and method of applying each nitrogen fertilizer, together with knowledge of its effect on plant nutrition, should be obtained first in order to establish the proper basis for determining comparative or relative fertilizing efficiency. Data of this character seem necessary in making possible the discovery of those principles which should serve to guide one in selecting fertilizers that will best meet the needs of the crops, and which should serve to guide one in applying the right kind of fertilizer at the proper time and in the best manner.

Commercial v. legume nitrogen. The problem of commercial versus legume nitrogen is one that lies mostly in the field of economics. In supplying crops with nitrogen, four courses are open: (1) the use of crop residues and farmyard manures; (2) the use of leguminous green manures; (3) the use of commercial nitrogen, together with the use of nonleguminous green manures to aid in maintaining soil organic matter; and (4) the use of any or all materials mentioned, as conditions or circumstances might indicate.

PHOSPHATE FERTILIZERS

The principal fertilizing ingredient in phosphatic materials may be expressed as "phosphorus" (P), "phosphorus pentoxide" or "phosphoric acid" (P_2O_5), and "bone phosphate of lime"

(B.P.L.). *Equivalents* may be shown as follows: 7 percent phosphorus (P) = 16 percent phosphorus pentoxide (P_2O_5) = 35 percent bone phosphate of lime (B.P.L.). Conversion factors are: $P \times 2.3 = P_2O_5$; $P \times 5 =$ B.P.L.; $P_2O_5 \times 0.4366 = P$; B.P.L. $\times$ $0.4578 = P_2O_5$; and B.P.L. $\times 0.2 = P$.

The principal fertilizing materials that are the main carriers of phosphorus are named in the accompanying table:

PRINCIPAL PHOSPHATIC FERTILIZING MATERIALS

NAME	Phosphorus Content		Availability of the Phosphorus
	Element P	Equivalent as P_2O_5	
	Percent	*Percent*	
Superphosphates.....	7–20½	16–47	Readily available
Steamed bone meal*..	10–14	23–32	Medium available
Dissolved bones......	6½–7	15–16	Readily available
Basic or Thomas slag.	4–11	9–25	Less available than bone meal
Rock phosphate......	11.8–14	27–32	Difficultly available

* Bone meal and dissolved bones also contain from 1 to 3 percent nitrogen.

Superphosphate was the first chemical or artificial fertilizer made (Ch. 1). Ordinary superphosphate is made by treating ground rock phosphate with sulphuric acid, in order to convert the insoluble calcium fluorphosphate, which has the empirical formula, $3Ca_3(PO_4)_2 \cdot CaF_2$, into available or water-soluble monocalcium phosphate, $CaH_4(PO_4)_2$. In addition, there are formed calcium sulphate ($CaSO_4$) and a small quantity of dicalcium phosphate, $Ca_2H_2(PO_4)_2$. For composition of Florida superphosphate, see Figure 98, first vertical line to the left.

Double, treble, or triple superphosphates are more recent products, containing from 40 to 45 percent P_2O_5. They are prepared by treating rock phosphate with liquid phosphoric acid (H_3PO_4). The process is carried out in two stages, first with weak sulphuric and then with phosphoric acid.

Superphosphates, as such, are commonly used for cereal crops, cotton, Indian corn, rutabagas, and potatoes. It is necessary to fertilize crops grown on certain soils with superphosphate; such soils are exhaustively cropped soils, heavy clays, acid soils, and peat and muck soils.

Steamed bone meal consists of ground steamed bones. Bones from meat-packing plants are steamed, or otherwise treated to remove fat and gelatin. After this treatment the bones crumble

easily, and are ground for fertilizer. The phosphorus compound in bones is called "calcium carbonato-phosphate" which has the empirical formula, $3Ca_3(PO_4)_2 \cdot CaCO_3$.

Bones were used in a limited way as a fertilizer in ancient times. Their use on cultivated lands is mentioned by early English writers from the middle of the seventeenth to the beginning of the nineteenth centuries. The value of "bone dust" for restoring the "life" of exhausted soils was recognized in eastern United States during the early years of 1800, when bones were gathered and pounded into "dust" for fertilizer. Bone meal is regarded as a most valuable fertilizer, especially by gardeners and truck growers, and for greenhouse use.

Dissolved bones, acidulated, or "vitriolized" bones are made by treating bones with sufficient sulphuric acid to dissolve about half of the phosphate. This material may be used for the same purposes as ordinary superphosphate.

Basic slag is obtained as a by-product in making steel from pig iron. In the processes (open-hearth and Bessemer), phosphorus is withdrawn from the molten phosphorus-containing iron in the presence of air and lime. Pulverized slag was first tested for fertilizing value in England in 1884, and thereafter it gradually came into use. This material is much used in European countries and to some extent in eastern United States. In England it has proved to be most valuable fertilizer for lands in grass. It may also be used on cultivated lands, especially on clayey soils and wet lands. It may be placed in contact with seeds.

Rock phosphate consists of finely ground natural phosphate rock. The principal deposits of phosphate rock are in Idaho, Florida, Montana, Utah, Wyoming, Tennessee, Arkansas, South Carolina, Kentucky (U.S.); Quebec, Ontario (Can.); Algeria, French Morocco, Tunisia (N. Af.); Russia; Nauru and ocean islands (Pacific); Egypt; and Makatea Island.

Owing to the fact that the phosphorus in rock phosphate is in a form not easily available to crops, the material gives best results when it is applied with manure, plowed under with green manure, and when thoroughly incorporated into soils, especially those that are acid and rich in organic matter. Especially finely divided rock phosphates, known as "colloidal phosphate" and "lime phosphate," offer an advantage, in that their particles can be more thoroughly distributed and incorporated into soils. The addition

of sulphur to a soil may greatly increase the availability of phosphorus in rock phosphate, as Brown and Gwinn (1917) have demonstrated in Iowa.

From comparative tests in which rock phosphate and superphosphate were used in the ratio of 2 to 1, Roberts (1930) has reported as good results with rock phosphate as with ordinary superphosphate on some Kentucky soils, both limed and unlimed. Bauer (1930) has suggested the following reasons why crops on some of the Illinois experimental fields have not responded to applications of rock phosphate: (1) Rock phosphate cannot be effective on liberally or excessively limed soils; (2) it may not be an effective carrier of phosphorus; (3) it was not applied properly; (4) materials used were not of the proper degree of fineness; (5) utilization of applied phosphorus by crops was delayed by deep-rooting legumes; and (6) many Illinois soils, under present conditions, seem to be able to supply crops with sufficient phosphorus to meet normal needs. On some soils, in the long run, these two forms of phosphate, when compared in equivalent quantities, may give about equal results.

Rock phosphates are used mainly for making superphosphates.

Soil phosphorus first to be replenished. The importance of phosphate fertilizers is indicated by the fact that in most cropped soils phosphorus is usually the first nutrient element to be replenished. This fact has been found to be true in the agricultural history of every country. It is for this reason that the first commercial fertilizers used are commonly phosphatic materials. The phosphorus content of most soils is not large (Ch. 4).

Fixation of phosphorus in soils. Phosphorus is an acid-radical or anion element, and is therefore not included in soil base-exchange reactions. Nevertheless, phosphorus is stably fixed in soils; but in some strongly acid soils with active aluminum and iron compounds, it may become fixed in forms not easily soluble or available to plants. Conner (1930) found that, on light-colored silt loams, one application of superphosphate at the rate of 1,000 pounds per acre once in 9 years was as effective as three applications at the rate of 333⅓ pounds per acre once in 3 years.

Under normal conditions, soil phosphorus suffers comparatively slight losses by drainage waters (see Index).

Under both natural and cultivated conditions, phosphorus tends

to accumulate in soils near the surface or in the topsoils. Roots absorb more or less phosphorus in the deeper layers of soils; and when plant residues decompose and the organic matter mineralizes, the phosphorus remains in the topsoils. Phosphate fertilizers are usually applied to the surface of soils and mixed into the tilled part, where the phosphorus becomes fixed. Movement of phosphorus to lower depths is usually very slow.

The factors of phosphate fixing in soils include texture, structure, reaction, and absorption capacity. Stephenson and Chapman (1931) found that, in soils which varied in texture from light to medium and which had received from 1 to 30 or more annual applications of phosphatic fertilizers, appreciable quantities of phosphorus had penetrated to depths greater than 1 foot; whereas in heavy-textured soils, little or no downward movement occurred. Manure phosphorus tends to move downward more rapidly than that of superphosphate. There seems to be a tendency for phosphorus to move downward more rapidly when heavy rather than when light applications are made. Considerable phosphate may move downward as fine particles, as the result of heavy applications of very finely divided rock phosphate. Calcareous soils, particularly those of arid and semiarid regions, have strong fixing power for phosphorus.

Calcium and availability of phosphorus. There are important relationships between calcium and magnesium in soils and the availability of native soil phosphorus and that applied in phosphatic materials. In humid regions, it is recognized that crops on soils which naturally contain adequate supplies of calcium and magnesium usually are able to obtain more phosphorus than those growing on acid soils; and that on most acid soils, the use of lime with superphosphate aids in keeping the applied phosphorus in readily available forms. Calcium is the most important basic element in controlling the concentration of phosphorus in soil solutions of neutral and slightly acid soils. In some acid soils, which contain hydrous oxide of iron that reacts readily with phosphorus, lime is not fully effective in preventing the fixation of phosphorus in insoluble forms. In alkaline-calcareous soils, the factors of availability of phosphates are carbonic acid and soil reaction.

Two types of soil conditions have been described with respect to calcium, to account for the ineffectiveness of rock phosphate as a fertilizer. They are:

1. In developing the observation made by Tschirikov (Russ., 1914), that plants with much calcium respond readily to phosphate, Truog (1916) found that plants having strong "feeding powers" for difficultly available phosphorus, such as that in rock phosphate, have high calcium contents. His supposition was that such plants cause the phosphorus in the insoluble rock phosphate to become available only as they remove calcium carbonate and bicarbonate from around the particles of rock phosphate, thus allowing solubility of the particles. In sand cultures, Bauer (1920) has increased the yields of Indian corn, fertilized with rock phosphate, by leaching the calcium bicarbonate that had accumulated in the mediums that resulted from greater utilization of phosphorus than calcium by the plants. Bauer compared this action with the conversion of insoluble phosphate into soluble forms, in the following way: Solubility of insoluble tricalcium phosphate consists essentially in removing two thirds of the calcium to form monocalcium phosphate. When one third of the calcium is removed, dicalcium phosphate is formed. Accordingly, when an acid soil is liberally or excessively limed, the added calcium tends to prevent the removal of calcium from any tricalcium phosphate that may be applied.

In reference to this question of the "feeding power" of crop plants, Davis, Hoagland, and Lipman (1923) have called attention to the importance of the carbon dioxide that is evolved from the roots of different plant species.

2. The other soil condition that may influence the effectiveness of rock phosphate has been described by Ford (1932-1933). He worked with some Kentucky soils in which phosphorus is readily fixed as insoluble iron compounds and on which lime had effected negative response of crops to rock phosphate (see Index). He concluded that lime does not act sufficiently in preventing the formation of insoluble phosphorus compounds to offset its effect in decreasing the solubility of rock phosphate.

Reversion of superphosphate by lime. It has long been taught that lime will revert superphosphate and thereby decrease its fertilizing value. Several investigators have found that the availability of superphosphate is not impaired when pulverized limestone is mixed with it. Conner (1930) has found by pot tests that availability of superphosphates is not adversely affected when calcium carbonate or silicates of iron and aluminum are mixed with it, as indicated by first crops of barley and tomatoes. Hudson (N. Z., 1930) has demonstrated that impairment of germination of turnip seeds by contact with superphosphate can be almost entirely prevented by mixing the phosphate with equal weight of ground limestone about 7 days before it is used, without reducing its fertilizing value to any appreciable degree. MacIntire and Shuey (1932)

found that dolomite or pure limestone can be mixed into superphosphate for immediate use without any appreciable formation of insoluble phosphorus compounds.

POTASH FERTILIZERS

The fertilizing constituent of potassic materials may be expressed as potassium (K) and potassium oxide, or "potash" (K_2O). *Equivalents* may be expressed as follows: 41½ percent potassium (K) = 50 percent potassium oxide, or "potash" (K_2O). Conversion factors are: $K \times 1.2 = K_2O$; and $K_2O \times 0.83 = K$.

Liebig placed considerable emphasis upon the nutritive values of "salts of the alkalies," but he did not determine which of these alkalies plants needed most. Shortly after 1852, Lawes and Gilbert (Eng.) showed by field experiments that, of the alkalies, potassium had the most value in plant nutrition.

For a long time potash needs were met through the use of manure, wood ashes, ashes of seaweeds, and common salt. The Stassfurt potash deposits in Germany, which were discovered in 1857, came to be worked in 1860; but little use was made of these potash salts by farmers until after 1890.

The Stassfurt mines have long been the main source of potassium salts. In 1928 Germany produced 1,860,100 tons of "potash" (K_2O), or about three fourths of the world's supply, and consumed two fifths of all potash fertilizers. During the same period, France produced 450,400 tons of "potash" (K_2O); Poland, 63,600 tons; the United States, 59,800 tons; Spain, 43,000 tons; and British India, 5,000 tons.[3]

Until 1914, the Stassfurt mines produced practically all the potassium salts of the world. During the World War other sources were exploited in various countries, including flue dust, industrial wastes and residues, seaweeds, certain natural deposits of potassium salts and brines, and potassium-containing rock minerals. The important potash-producing deposits include those of the middle Rhine River country in Europe (Alsace-Lorraine); southeastern New Mexico-western Texas; Searles Lake, Trona, southern California; eastern Carpathian Mountains, Austria; Ural Mountains region, U.S.S.R.; and northeastern point of Spain. There are undeveloped sources in Chile, Peru, and Brazil. Among other possible sources of

[3] International Yearbook of Agricultural Statistics.

potassium salts are the Dead Sea, the enormous deposits of leucite in Wyoming, the potash shales of Georgia, and the greensand (glauconite) of New Jersey.

The sea may be regarded as an enormous reservoir of potassium salts. It has been estimated that there are 1,141,000 millions of tons of potassium sulphate in the oceans. For a time this store was drawn upon commercially in a very limited way by means

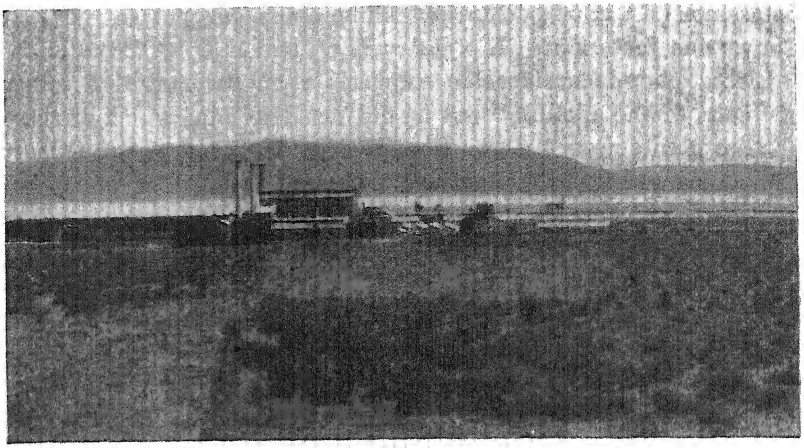

Fig. 96. Potash and borax plant and Searles Lake, Trona, Calif.

of "salt gardens" on the coast of France; but these gardens lost their industrial importance upon the development of the Stassfurt deposits.

The principal potash fertilizers are named in the table at the top of p. 425.

Potassium salts from the Alsace mines differ from those of Stassfurt, in that they consist of potassium and sodium chlorides only. In the Alsace mines the native salt is principally sylvinite. The potassium salts of the Stassfurt deposits occur natively in carnallite, kainite, and sylvinite (as chloride) and in kieserite and polyhalite (as sulphate). The principal product of the Stassfurt mines is potassium chloride. The product derived from the brine of Searles Lake is also chloride, of from 96 to 98 percent purity, and is used in western United States.

Kainite (kā'ĭ-nīt) is a crude potassium salt unprepared except for grinding. Twenty-percent potash salt is low-grade muriate of

Potash Fertilizers and Percentage Composition of Principal Constituents

Fertilizer	Grade or Purity	Potassium Chloride (KCl)	Potassium Sulphate (K_2SO_4)	Magnesium Sulphate ($MgSO_4$)	Magnesium Chloride ($MgCl$)	Sodium Chloride (NaCl)	Potassium	
							Element (K)	Equivalent as K_2O
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Muriate of potash......	80–85	80–85	—	0.0 to 0.04	0.0 to 0.03	13.0 to 18.5	41.5 to 52.3	50–63
Sulphate of potash......	90–96	0.3–1.6	90–96	0.7 to 2.7	0.4 to 1.0	0.2 to 1.2	40.3 to 43.0	48.6–51.8
Kainite.......	14	22.2 to 25.4	—	0.0 to 20.8	0.1 to 2.3	44.6 to 60.7	12 to 16.5	14.5–20
Potash salts ...	20	31.7 to 34.8	—	0.0 to 12.0	0.1 to 4.2	41.8 to 52.3	16.6 to 18.3	20–22
Potash salts ...	30	47.5 to 50.7	—	0.0 to 10.2	0.0 to 4.2	24.1 to 27.3	24.9 to 26.6	30–32

potash, whereas high-grade potash salt is obtained by refining kainite by recrystallization.

Wood ashes and soot. Wood ashes vary widely in the quantity of potassium they contain (as carbonate)—from 2 to 10 percent, or equivalent as "potash" (K_2O), from 2.5 to 12 percent. When thoroughly leached they have little or no fertilizing value. Hardwood ashes are usually richer in potassium than those made from soft woods. Ashes resulting from burning woods at high temperature contain much less potassium than those produced in burning woods at comparatively low temperatures, as in kitchen ranges and brush heaps. In addition to potassium, wood ashes contain from 50 to 75 percent carbonates of lime ($CaCO_3$) and magnesia ($MgCO_3$).

Soot consists principally of finely divided particles of carbon that are deposited in flues as a result of imperfect combustion. Owing to its physical condition and absorptive property, it is usually rich in ammonia which has been absorbed from the combustion gases. The nitrogen content of soots may vary from ½ to about 6 percent.

Other potassic materials. Among other potassium fertilizing materials are those in the following table.

MISCELLANEOUS POTASSIC FERTILIZING MATERIALS

Material and Source	Potassium Content	
	Element (K)	Equivalent as K_2O
	Percent	*Percent*
Tobacco stems	3.3–5	4–6
Flue dust from cement industry	10	12
Flue dust from iron blast furnaces	16.6	20
Waste from beet-sugar factories	16.6	20
Kelp potash (muriate) from seaweed	28	34
Wool washings from wool industry	10–41.5	12–50

General use of potash fertilizers. All the potassium salts are soluble in water, and hence the potassium in them may be regarded as being immediately available. Whether one or the other potash fertilizer is used is determined mainly by cost of material, kind of crop, and content of ingredients other than potassium. Muriate of potash (KCl) is the most abundant and commonly used material. Ordinarily, the chlorine in it produces no particularly harmful effects; therefore, under humid conditions, muriate is practically as effective as the sulphate. Greater quantities of chlorine, in proportion to potassium, may be injurious to crops like tobacco and potatoes. The magnesium of potash salts and sulphate of potash-magnesia has special value in meeting deficiencies of this element. The potassium-magnesium mixture has proved to be valuable in effecting control of "sand-drown," or magnesium hunger, in tobacco (Ch. 9).

Potassium salts may be used to fertilize practically all kinds of crops, being specially important for potatoes, sugar beets, mangels, tobacco, and leguminous crops, particularly clover. Potash fertilizers are especially needed on long-cropped soils, peat soils, and those that contain much sand, chalk lands like those in England, and alkali soils of humid regions.

Soils that are composed largely of silt and clay usually contain large quantities of potassium (Ch. 4); but in many of them, notably the clayey types, the potassium is not readily available. It would seem that under such conditions the remedy consists in liberating this soil potassium by growing sweetclover for green manure, rather than in adding potash fertilizers in suitable forms and adequate quantities to meet crop requirements. According to Bauer (1930), factors other than simply liberation are involved, as results obtained on 28 Illinois experiment fields seem to indicate.

Crops on the less fertile fields have responded most, and some of the more productive soils have shown marked res[illegible] to applications of potash fertilizers.

In either grain or livestock farming, considerable soil potassium can probably be made available through the use of crop residues, barnyard manure, and green manures. Whether adequate quantities can thus be made available to meet the current needs of crops can be determined only by field tests. In this manner may also be determined whether the simple method of adding fertilizer is more economical and profitable than any method of making soil potassium available.

Fixation of potassium in soils. Being a positive ion, or cation, potassium is one of the elements concerned in soil base-exchange. As this element can readily be fixed in base-exchange compounds, it may be desirable to incorporate potash fertilizers into soils in order to effect proper distribution, or to place them within the zones of feeding roots; otherwise the potassium may become fixed at points of contact with soil material out of reach of the roots. Top-dressing with potash fertilizer may result in the accumulation of potassium at or near the surface; this may become an important problem in fertilizing fruit trees. Exceptions are to be found in soils that contain considerable sand or comparatively small quantities of base-exchange materials, and in soils made acid through continual use of sulphate of ammonia (Ch. 16). On such soils added potassium may suffer loss by leaching.

Page and Williams (Eng., 1925), Merkle (1928), Lyon and coworkers (1930), and others have found that continual use of potash fertilizers over a period of years may result in an increase of exchangeable potassium. Inasmuch as base-exchange is governed by the chemical law of mass action and equilibrium, the degree to which soils may absorb added potassium is determined by soil texture and reaction, the nature of potassium in regard to its valence and hydration, the quantity of potassium salts added, soil ion-exchange capacity, and whether much rain follows application.

Soil acidity may depress the absorption of potassium. On plot 32 of the Jordan Soil-fertility Plots of Pennsylvania, laid out in 1881, Merkle (1931) found that soil acidity (pH 4.55, developed from use of sulphate of ammonia) prevented the accumulation of added potassium, probably because of the great excess of hydrogen ions in the soil solution and base-exchange materials (Ch. 4).

The fact that exhaustive cropping decreases exchangeable potassium in soils indicates that such potassium is an important factor in the nutrition of crop plants. Evidence concerning added potassium indicates that some of the potassium absorbed may change into comparatively insoluble or nonexchangeable form.

Lyon and co-workers (1930) found that applications of potash fertilizer (sulphate) resulted in an increase in the quantities of calcium and magnesium removed in the drainage waters, but it did not cause any additional loss of potassium. The potassium was absorbed at the expense of the calcium and magnesium. Thus, an unnecessary use of potash fertilizer may cause considerable losses from soils of these two important basic elements.

MIXED AND CONCENTRATED FERTILIZERS

Mixed or compound fertilizers are mixtures of different fertilizing materials which contain either two or three of the major nutrient elements. Mixtures that carry all three elements—nitrogen, phosphorus, and potassium—are called "complete" fertilizers.

Mixed fertilizers are commonly designated by their analyses, as 4–8–4, 0–12–12, 15–0–15, and 20–20–0, in which the analyses are of nitrogen (N), "phosphoric acid" (P_2O_5), and "potash" (K_2O), respectively. Ordinary superphosphate is sometimes expressed as 0–16–0. These analyses also express units of fertilizing constituents; for example, a 4–8–4 mixture contains 16 units. One percent (on a ton basis), or 20 pounds, constitutes 1 unit of N, P_2O_5, or K_2O.

In making mixed fertilizers, superphosphate is usually manufactured at the factory and the other materials are assembled and mixed in proportions necessary to obtain the analyses desired.

Mixed fertilizers may be made either by dry-mixing or wet-mixing. The former process consists in mixing dry materials in given proportions. In wet-mixing, organic by-product materials are mixed with rock phosphate and the whole is then treated with sulphuric acid.

The different materials that are mixed together must be chemically compatible in order to effect proper chemical and physical condition, prevent loss of nitrogen, and prevent the reversion of soluble phosphorus compounds to difficultly available and insoluble forms.

In accord with regulatory laws, fertilizer manufacturers must state on fertilizer bags or on tags attached thereto the fertilizing ingredients, their content in percentages, and solubility. The sources of the ingredients are not included, and the solubility is usually stated only for phosphoric acid (P_2O_5).

Home-mixing of fertilizers. The fertilizer industry of the United States is based largely on ready-mixed or factory-prepared products. However, farmers may prepare their own fertilizers. Mixing fertilizing materials on farms is called "home-mixing," a practice that has always had its advocates. The mixing process is comparatively simple. The materials used are spread on a clean surface in layers, usually the most bulky first, and are thoroughly mixed by shoveling. It is important that the proper materials be mixed. Chemically compatible and incompatible materials are indicated in Figure 97.

In home-mixing, materials may be put together to duplicate a successful mixture or to make mixtures to suit soil conditions and meet crop requirements. To illustrate:

A 4–8–4 mixture may be prepared by using the following materials:

	Quantity of Material Required Pounds
Nitrogen required per ton, 80 pounds	
Let nitrate of soda (16-percent) supply 28 pounds.........	178
Let sulphate of ammonia (20½-percent) supply 26 pounds..	127
Let cottonsed meal (7-percent) supply 26 pounds..........	380
"Phosphoric acid" required per ton, 160 pounds.	
Let superphosphate (16-percent) supply the total	1,000
"Potash" required per ton, 80 pounds.	
Let muriate of potash (50-percent) supply the total	160
Filler (pulverized peat) to bring total to 2,000 pounds	155
	2,000

If this mixture is used without filler, it cannot be called a 4–8–4 fertilizer, owing to the fact that units of fertilizing constituents are based on the ton weight of 2,000 pounds. Without the filler, the mixture would analyze 4.3 percent N, 8.7 percent P_2O_5, and 4.3 percent K_2O. On the basis of fertilizing constituents, 1,845

pounds of such a mixture (without filler) would be equivalent to 2,000 pounds of a 4–8–4 fertilizer.

Ammoniated superphosphate. The term "ammoniated phosphate" originated during the World War (1914-1918), when, owing to scarcity of potassium salts, fertilizer manufacturers found it necessary to put out mixtures that contained nitrogen and phosphorus only. Prior to that time the term "ammoniates" was used for all carriers of nitrogen.

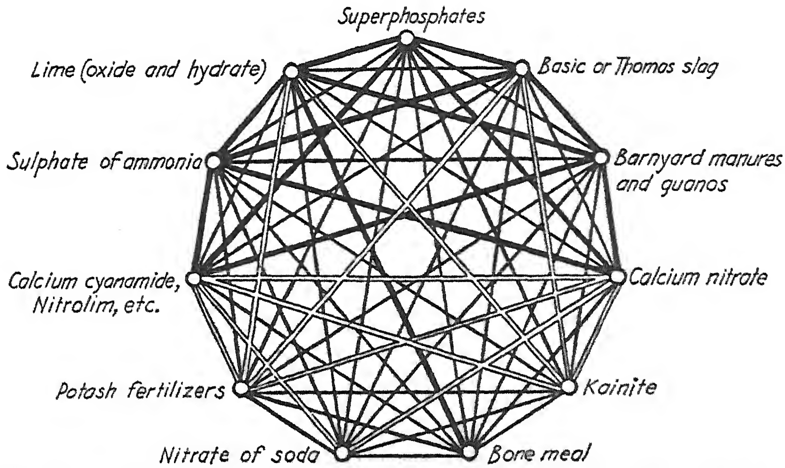

Fig. 97. Chemically compatible and incompatible fertilizer materials. The heavy lines connect the names of materials that should not be mixed. The double lines show what materials, when mixed, should be applied immediately after mixing. The single lines connect the names of materials that may be mixed at any time.

In 1927, the manufacture of ammoniated superphosphate began. It is produced by treating dry superphosphate with synthetic ammonia (NH_3) either in the anhydrous or aqueous form, usually the former. Urea-ammonia liquor is also used for this purpose.[4] The product is used as a constituent of mixed fertilizers. The changes effected in superphosphate by ammoniation have been studied by Keenen (1930) and Jacobs and co-workers (1930). These changes are indicated in Figure 98.

Ammoniation of superphosphate may be regarded as a most significant development in the fertilizer industry. Its economic im-

4 Urea-ammonia liquor is essentially a solution of crude urea in aqueous ammonia. It contains 45.5 percent nitrogen—one third in urea (chemical organic) and the other two thirds is inorganic nitrogen.

portance may be summarized as follows: (1) Anhydrous ammonia and urea-ammonia liquor are very cheap forms of nitrogen available to the fertilizer industry; (2) ammoniation of superphosphate provides a means for the fixation of large quantities of synthetic ammonia without increasing the use of sulphuric and other acids; (3) it greatly improves the mechanical condition and storing qualities of superphosphate and mixed fertilizers; (4) it neutralizes acids in superphosphate; and (5) it reduces rotting of fertilizer bags to the minimum.

Although ammoniation of superphosphate marks a significant advancement in the fertilizer industry, absorption of ammonia (NH_3) by superphosphate had been known since 1873, when McDougall protected the idea with a patent. The use of ammonia gas in fertilizers was suggested 6 years earlier by Way (Eng., 1867). After 1873, ammoniation developed rapidly; but when anhydrous synthetic ammonia became available in 1927 at a considerably lower price than other forms of ammonia, the process soon became a most important one commercially, and its commercial importance was greatly increased when urea-ammonia liquor appeared on the market in 1932. Inasmuch as precipitated tricalcium phosphate, which may be formed in ammoniation, is a valuable fertilizing material, it may be possible to add about 3 percent of nitrogen to ordinary superphosphate through the use of anhydrous ammonia, and about 4.5 percent through the use of urea-ammonia liquor.

Low- and high-analysis fertilizers. Fertilizers that contain less than 14 percent of fertilizing ingredients, like 2–8–2, are classed as *low analysis;* from 14 to 23, *normal analysis;* those that contain from 24 to 36 percent, like 4–8–16, are classed as *high analysis;* and those that contain more than 36 percent are classed as *concentrated.* Inasmuch as concentration is an important factor of economy in fertilizer practice, the higher-analysis materials and mixtures are regarded as *standard fertilizers.* The trend in the manufacture of fertilizers in recent years has been toward more extensive use of concentrated chemical compounds.

Concentrated fertilizing materials. The successful commercial production of synthetic ammonia and the introduction of double or treble superphosphate have led to increased concentration of fertilizing materials and fertilizers. Many new highly concentrated compounds have been made, which contain one, two, and all three

of the major fertilizing elements. Four of these new materials have already been described: namely, ammonium nitrate, urea, Calurea, and treble superphosphate. In the table on the next page

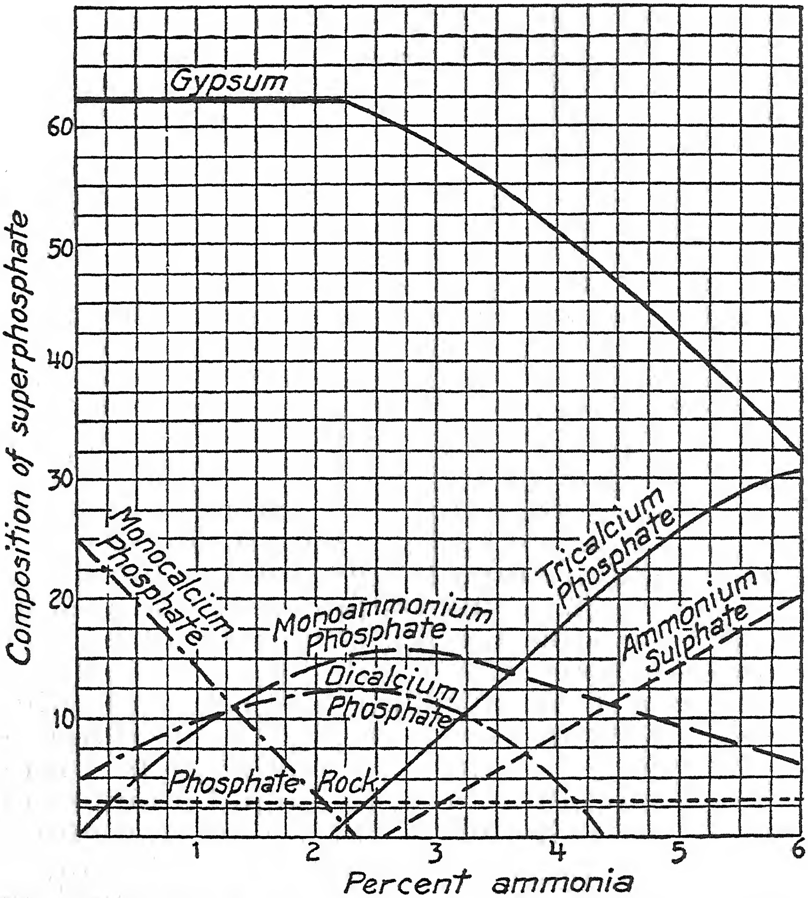

Fig. 98. Changes in the composition of Florida pebble superphosphate caused by ammoniation.

are named some concentrated materials which carry two or three fertilizing elements.

Monoammonium phosphate ($NH_4H_2PO_4$) is a very stable, non-hygroscopic, white salt with an acid reaction. It is prepared by neutralizing phosphoric acid with ammonia (nitrogen, air-derived). It is a granular product and has excellent handling and fertilizing qualities. All its nitrogen is in the ammonium form.

CONCENTRATED COMPOUNDS WITH TWO OR THREE FERTILIZING ELEMENTS

Name	Nitrogen (N)	Phosphorus		Potassium	
		Element (P)	Equivalent as P_2O_5	Element (K)	Equivalent as K_2O
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Monoammonium phosphate	11–12	26.9	61.7	—	—
Ammo-Phos, A and B *	11–16	21–8.7	48–20	—	—
Diammonphos	21	23	53	—	—
Leunaphos	20	8.7	20	—	—
Potazote	9.9–11.5	—	—	20–16.6	20–24
Potassium ammonium nitrate	16–16.5	—	—	20.75–23	25–28
Potassium nitrate	13.5	—	—	38	46
Nitrate of soda-potash (Nitrapo)	14–14.8	—	—	10–13	12–16
Nitrophoskas	15–16.5	4.8–13	11–30	12.5–22	15–26.5

* Ammo-Phos-Ko, an American product, consists of varying proportions of Ammo-Phos and potassium sulphate. One of the products contains 12 per cent nitrogen, 24 percent "phosphoric acid" (10.5 percent P), and 12 percent "potash" (10 percent K).

Ammo-Phos A, which is crude monoammonium phosphate, analyzes 10.7 percent nitrogen and 46 percent P_2O_5. Ammo-Phos B is made by adding ammonia to a mixture of phosphoric and sulphuric acids. The resulting product is a mixture of ammonium sulphate and monoammonium phosphate, and it contains 16.5 percent nitrogen in the ammonium form and 20 percent P_2O_5.

Diammonphos, $(NH_4)_2HPO_4$, is another combination of ammonia and liquid phosphoric acid. It is a white, slightly alkaline, nonhygroscopic, crystalline salt. In making this compound, about twice as much ammonia can be fixed per unit of phosphoric acid as in making monoammonium phosphate. As the formula indicates, all the nitrogen is in the ammonium form.

Leunaphos, a 20–20–0 mixture, is a German product prepared by mixing diammonium phosphate and ammonium sulphate in the proportion of 2 to 3.

Potazote, a French product, may contain either 9.9 percent nitrogen and 24 percent K_2O or 11½ percent nitrogen and 20 percent K_2O. It is a product formed by treating sylvinite in a manner similar to the Solvay process. After the sodium is precipitated as sodium bicarbonate, the liquor contains a mixture of potassium and ammonium chlorides.

Potassium ammonium nitrate is a mixture of potassium chloride and ammonium nitrate. Kaliammosalpeter, a German product, carries 16 percent nitrogen and 28 percent K_2O. Nitropotasse, a French product, carries 16.5 percent nitrogen and 25 percent K_2O.

Potassium nitrate was known to possess plant-stimulating qualities as early as 1656. It was then called "niter" (Ch. 9). Much of the commercial potassium nitrate is a product of double decomposition, involving either sodium nitrate and potassium chloride or calcium nitrate and potassium sulphate. A product made in Germany is produced by treating potassium chloride with nitric acid.

Nitrate of soda-potash is a mixture composed of about three fourths natural nitrate of soda and about one fourth natural potassium nitrate. It is obtained from the nitrate deposits of northern Chile. In some places this product is sold under the trade name of Nitrapo.

Nitrophoskas constitute a series of complete, concentrated fertilizing materials, including the following mixtures: (I) 15–30–15 (muriate); (II) 16.5–16.5–20 (muriate); (III) 15.5–15.5–19 (sulphate); and (IV) 15–11–26.5 (muriate). They are all made of diammonium phosphate, ammonium nitrate (added as a hot solution), and potassium chloride or potassium sulphate, which are subjected to a graining treatment in the process of mixing. In the mixing there are formed some potassium nitrate and ammonium chloride or ammonium sulphate.

Advantages and disadvantages of concentration. Concentration of fertilizing materials effects important economies in different ways. It reduces the bulk of material per given quantity of fertilizing constituents, it reduces transportation charges, it reduces the number of fertilizer bags, it calls for less storage space, and it reduces labor costs.

Certain disadvantages may attend the use of concentrated fertilizers in connection with their application, distribution, and purity. Their use calls for improved methods of application in order to effect proper distribution and placement, and also for more consideration regarding supplementary use of the trace-requirement elements.

The older fertilizers contained many substances and impurities which have since been found to be valuable ingredients, owing to their favorable effects on plant growth. Concentrated fertilizers, on the other hand, are characterized by a high degree of purity. On sandy soils, especially, deficiencies of certain trace elements will probably be observed sooner or later if only these pure materials are used (Fig. 99).

Attention has been called to the fact that certain calcium-free fertilizers, which on decomposition give rise to free ammonia, may cause injury to seedlings, especially in acid sandy soils (Ch. 19). The effects of diammonium and monoammonium phosphates, in this respect, have been studied by Willis and Piland (1930) who found that the use of the former material resulted in the greater degree of injury. Werner (Ger., 1930) has observed that on very

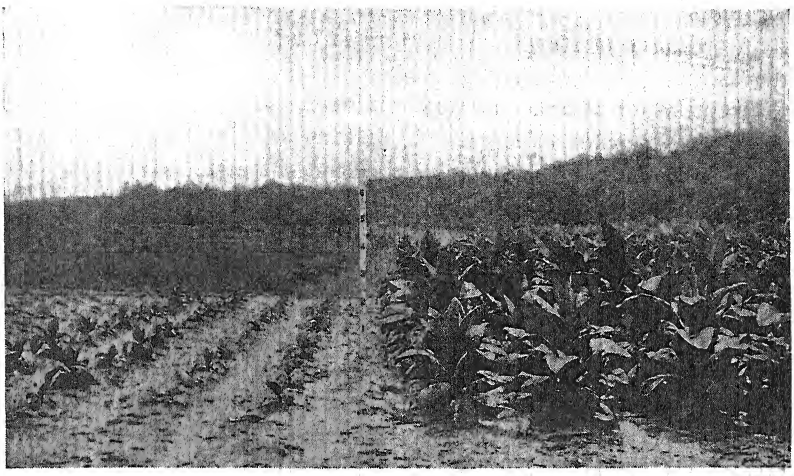

Fig. 99. Chemically pure concentrated fertilizer materials may lack certain necessary elements. Left (4 rows)—Tobacco on a soil that is deficient in calcium and magnesium, fertilized with a complete mixture of ammonium nitrate, ammonium sulphate, monoammonium phosphate, and muriate of potash (40, 64, and 80 pounds of N, P_2O_5, and K_2O, respectively, per acre), but which contained no calcium nor magnesium. Right—Tobacco plants that have received a fertilizer mixture of like analysis, but which contained calcium and magnesium. (Bur. Plant Industry, U. S. Dept. Agr.)

sandy soils with low absorption powers, Nitrophoska may produce ammonium carbonate which may cause loss of nitrogen and injury to seedlings, through the formation of free ammonia.

Important findings. Results of fertilizer experiments have shown the importance of three practical points regarding commercial fertilizers: (1) the addition of calcium, magnesium, and probably sulphur for greater efficiency; (2) the use of fertilizers that do not increase the acidity of acid soils, except in special cases; and (3) the use of highly acidic fertilizers on alkaline soils.

Injury from "burning." Direct injury (plasmolysis) to germinating seeds and to seedlings by contact with fertilizing materials is determined largely by the fertilizer's content of water-soluble salts. If high-analysis fertilizers are prepared from concentrated materials in such a way as to result in a higher proportion of soluble salts to fertilizing ingredients, danger of "burning" will be increased accordingly. On the contrary, there may be prepared concentrated mixtures that contain a much lower proportion of soluble salts, and hence can be used with less danger of burning than ordinary mixtures. This point is further discussed in Chapter 23.

Granulation of concentrated mixtures. Size and shape of particles have marked effects on the drilling and keeping qualities of many fertilizers, particularly the concentrated materials. In studying this problem, Ross and co-workers (1924-1931) have found that granulation of easily fusible materials like calcium nitrate, urea, and ammonium nitrate may be effected by spraying melts of each into a cooling tower. The droplets congeal in spherical particles as they fall. Most compound materials, however, cannot be melted without causing decomposition. In such cases, granulation involves dehydration of moistened materials by graining, rotary drying, and by letting the material fall in a dispersed condition in a drying tower. Without injuriously affecting the availability of the nutrient elements, granulation prevents the segregation of component ingredients, prevents caking, improves drilling qualities, and, in application, prevents blowing.

Comparative use of mixed fertilizers. Fertilizer practice in America differs somewhat from that in Europe, there being more general use of mixtures in America. Single-element fertilizers, notably phosphate and potash, are commonly used when soil conditions indicate their need; whereas nitrogen fertilizers are used singly as top-dressing, side-dressing, and in orchards and vineyards to meet normal requirements and special needs of crops, and to effect greater economy in the use of commercial nitrogen.

Inasmuch as exhaustive or continual cropping results in loss of the ability of soils to supply crops with adequate quantities of the major nutrient elements for normal yields, usually two or all three of these elements are required in varying quantities and proportions. For economic reasons mainly, American farmers com-

monly prefer to apply these necessary fertilizing elements all at the same time or in one operation.

Other points in favor of high-grade factory-made mixtures are their intimate admixture and drilling qualities. Points against them are the possibility of their containing low-grade materials and their unsuitability for particular soils and crops.

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REVIEW QUESTIONS

1. Why do some farmers conserve liquid manure for fertilizing purposes? How is this conservation accomplished?
2. When should farm manure be applied as top-dressing? Plowed under?
3. Gardeners have obtained best results with well-composted manures. Explain.
4. What is meant when stall manure is spoken of as an "unbalanced fertilizer"? How can it be "balanced"?
5. What are artificial farm manures? How made?
6. How is phosphorus being recovered from sea water for fertilizer use?
7. Compare the water-insoluble sources of nitrogen with those that are water-soluble in regard to composition and availability of the nitrogen.
8. What is meant by the direct synthetic-ammonia process in nitrogen fixation? Discuss its economic importance.
9. Which is the better form of nitrogen for fertilizer use, nitric or ammonic? Explain and give examples.
10. Describe the conditions of soils and crops that call for the use of different phosphates.

11. Should a farmer apply superphosphate on a field that has recently been limed? Explain.
12. Construct a sentence in which are used all the concepts that are indicated by "P," "P_2O_5," "B.P.L.," and the term "phosphoric acid."
13. Is it reasonable to believe that there must be immense deposits of potassium salts? (See Ch. 4.)
14. Describe the conditions of soils and crops that determine what kind of potash fertilizer should be used.
15. Name some advantages in using ready-mixed or complete fertilizers. Some disadvantages.
16. What are some of the advantages and disadvantages in using concentrated fertilizers?
17. What is the difference between concentrated and high-analysis fertilizers?
18. Formulate a principle that should guide one in the use of chemical fertilizers.

CHAPTER 22

FERTILIZERS, THEIR EFFECTS ON SOILS AND PLANTS

The response that a crop makes to a fertilizer is the result of the effects produced by the applied fertilizer on many interdependent factors. Soils and plants are the two principal factors on which fertilizer materials may produce very important effects other than increasing the supply of available nutrients and the yield of crops. The science and art of the use of fertilizers call for a knowledge of these effects.

EFFECTS OF FERTILIZERS ON SOILS

Inasmuch as soils are physical-chemical-biological complexes, a fertilizer material, especially if used continually, may produce profound changes in them. These changes may affect soil reaction, physical properties of clays, conservation of calcium and magnesium, reserves and availability of nutrient elements, toxic substances, and micro-organisms.

Physiological reaction of fertilizer salts. If plants in a water culture, in exchange of ions, absorb basic cations from the solution, such as Ca^{++}, Mg^{++}, and K^{+}, in greater proportion than they absorb acidic anions like NO_3^-, SO_4^{--}, and $H_2PO_4^-$, the result is an accumulation of negative or acidic ions in the culture solution, causing a change in reaction toward acidity. If, for example, the ammonium ions (NH_4^+) of ammonium sulphate are absorbed, sulphuric acid (SO_4^{--}) accumulates in the solution. Salts that cause accumulation of acids in culture solutions because of greater absorption of basic cations by plants are called "physiologically acid salts." Accordingly, fertilizers that produce acid effects in soils are commonly regarded as being physiologically acid. In contrast, there are salts whose acidic anions may be absorbed in larger proportion than their basic cations. These produce opposite effects, and are called "physiologically alkaline salts"; sodium nitrate ($NaNO_3$) is a good example.

Among the most important physiologically acid and alkaline

fertilizer salts are the nitrogen carriers. Those that carry only the basic or ammonium form of nitrogen (NH_4), like sulphate of ammonia, are physiologically acid; whereas those that carry only the acidic or nitrate form (NO_3), like nitrate of soda, are physiologically alkaline.

One of the most interesting nitrogen compounds, as well as one of the best sources of nitrogen for plants, is ammonium nitrate (NH_4NO_3) which carries both basic and acidic forms of nitrogen. In water cultures certain plants may absorb the two forms at about equal rate. When the ions are thus absorbed, this salt is *physiologically neutral.* In soils, however, it produces acid effects, owing to base-exchange action and nitrification of the ammonium cations. In soils, residues and plant absorption of ions are not the only factors involved; base-exchange action and nitrification of added ammonium ions are other factors which come into play in affecting soil reaction. This explains why a so-called "physiologically neutral" nitrogenous salt (in culture solutions) may prove to be an acidic fertilizer.

Effects of fertilizers on soil reaction. The effects of fertilizer salts on soil reaction were first studied by Mayer (Ger.) in 1881, when he sought to find out why crops did not give a more general response to potash salts. He concluded that potassium salts produced acid effects. But Kappen (Ger., 1927), finding that these salts produced no such effects, concluded that Mayer had erred. The action of sulphate of ammonia was studied by Wheeler in 1891, and of sulphate of ammonia and other fertilizers by subsequent investigators.

The permanent effect of a fertilizer on soil reaction is determined by chemical composition of the fertilizer, base-exchange, nitrification, plant absorption of applied nutrients (physiological), soil reaction, and soil leaching.

Ammonium salts and other compounds which give rise to ammonia are the most potent acid-forming fertilizer materials. Their action, in humid regions, may be illustrated by that of sulphate of ammonia. This action proceeds in three principal stages: (1) The ammonium ions (NH_4) displace calcium of the base-exchange complex, and the calcium combines with the sulphate anion (SO_4), forming calcium sulphate which becomes subject to leaching. (2) nitrification of the ammonium ions results in the displacement of them by hydrogen, and in the formation of nitric acid. (3) The

nitric acid may react with exchangeable calcium and/or magnesium, and form nitrates, which bring about a further increase of hydrogen in the soil base-exchange compounds.[1]

On the comparable basis of 1 unit of nitrogen (20 lb.), sulphate of ammonia, ammonium chloride, and monoammonium phosphate are the most acid in their effects, having an equal relative rating of 100. It has been found that to neutralize the acid formed in soils about 113 pounds of pure calcium carbonate, or the equivalent of from 150 to 200 pounds of ordinary pulverized limestone, are required for each 100 pounds of sulphate of ammonia used. According to Pierre (1933), the relative ratings of other acid-forming, nitrogen-containing fertilizers, based on 1 unit of nitrogen, and compared with sulphate of ammonia, are as follows: Leunaphos, 87; Leunasalpeter and Diammonphos, 67; Nitrophoskas, 43 to 60; urea and ammonium nitrate, 33; dried blood 32.7; cottonseed meal, 26; Calurea, 20; Peruvian guano, 18; and fish scrap, 2 to 17.

Cyanamid, nitrate of soda, calcium nitrate, and Calnitro are basic nitrogen fertilizers, having relative ratings, based on 1 unit of nitrogen, of 100, 63, 63, and 39, respectively. The basic effects of 100 pounds of Cyanamid is equivalent to about 62 pounds of pure calcium carbonate.

Some phosphates, like basic slag, are basic. Pierre (1934) found that, in general, superphosphate, rock phosphate, and monocalcium phosphate have no appreciable effects on soil reaction; whereas dicalcium and tricalcium phosphates are basic. Because of the ammonia, ammoniated superphosphates tend to increase soil acidity.

Ordinarily, under field conditions, potash fertilizers like muriate, sulphate, and kainite have little or no effect on soil reaction. Crowther (Eng., 1925) has observed that sulphate of potash has slightly increased the acidity of the subsoil of the more acid plots at Woburn.

Reaction of the medium may influence the effect of a fertilizer. Górski and Dabrowska (Pol., 1930) found that, in cultures, potassium chloride was physiologically acid at pH 5.7, and alkaline at pH 4.4; and that potassium sulphate was basic at pH 3.9. Pierre (1933) found that in soil materials having pH value of 4.2, superphosphate reduced acidity; at pH 5.3, it had but little effect on reaction; whereas at 6.2, it showed a tendency to increase acidity.

[1] PIERRE, W. H. NITROGENOUS FERTILIZERS AND SOIL ACIDITY: I. Jour. Amer. Soc. Agron., Vol. 20, No. 3, p. 265. 1928.

Acidic-basic balance of fertilizers. Pierre (1933) has shown that fertilizers that have an excess of acidic ions (anions) over basic ions (cations) increase soil acidity, whereas those that have an excess of basic ions reduce acidity. He has suggested this balance: SO_4^{--}, Cl^-, half the nitrogen, and one third of the phosphate anions versus Ca^{++}, Mg^{++}, K^+, and Na^+ cations. Because of base-exchange action and nitrification of ammonium ions, nitrogen is acidic. Only about half the nitrogen, however, is effective, owing to plant action. This is shown in the fact that sulphate of ammonia develops only three fourths of its potential acidity on a cropped soil, and is also shown in the basic action of sodium and calcium nitrates.

Poultry and barnyard manures have been found to be slightly acidic in their effects, whereas tobacco stems are basic. The effects of tankages on soil reaction may be acidic or basic, depending on kind and grade. Fertilizer materials may be so mixed as to be neutral in their effects; examples of such mixtures are 70 percent nitrate of soda and 30 percent sulphate of ammonia; 54 percent nitrate of soda and 46 percent urea; 64 percent nitrate of soda and 36 percent Leunasalpeter; 65 percent calcium cyanamide or Cyanamid and 35 percent sulphate of ammonia; 52 percent Cyanamid and 48 percent urea; and 58 percent Cyanamid and 42 percent Leunasalpeter.[2]

Effects of fertilizers on clays. The physical properties of clays are determined principally by their chemical nature or constitution, as indicated by the changed character of a given aluminosilicate complex when it is saturated with hydrogen, and when a sodium clay is involved (Ch. 4). The acidifying action of certain fertilizers causes the formation of acid clays which are rather easily dispersed. Clay-containing soils that are made strongly acid by acid-forming fertilizers are characterized by poor physical condition and infertility or low producing power.

Sodium residue may cause the development of sodium clays under certain conditions—particularly when it is present in considerable concentration and when active calcium and magnesium are not present. These sodium clays disperse more easily than acid clays. Sodium-clay subsoils form impervious layers which greatly impair soil drainage or may prevent it entirely (Ch. 4). Moreover, sodium seems to destroy base-exchange properties. A

[2] PIERRE, W. H. NITROGENOUS FERTILIZERS AND SOIL ACIDITY: II. Jour. Am. Soc. Agron., Vol. 20, No. 3, p. 271. 1928.

conspicuous effect of continued use of nitrate of soda on the Jordan Soil-fertility Plots, as reported by Merkle (1932), is the destruction of a part of the soil absorptive complex.

Inasmuch as base-exchange is governed by the chemical law of mass action and equilibrium, accumulation of sodium in soil base-exchange compounds may be controlled by providing soils with active calcium and magnesium. On equal basis, calcium is much more effective than sodium in competing for exchangeable basic elements; hence calcium may depress the accumulation of sodium to the minimum. From studies of neutral Rothamsted soil by Page and Williams (1925), of the soil of the Jordan Soil-fertility Plots of Pennsylvania by Merkle (1928), of limed and unlimed plots at Wooster, Ohio, by Schollenberger and Dreibelbis (1929), and of other soils by other investigators, the following general conclusions may be drawn regarding the accumulation of sodium in soils through continual use of nitrate of soda: (1) In soils of humid regions which are well supplied with lime (Ca and Mg), no harmful accumulative effects from sodium may occur even with rather heavy applications of nitrate of soda; (2) no appreciable accumulation of sodium results from ordinary or rational applications of nitrate of soda; and (3) there probably is little danger of soils becoming injuriously loaded with sodium when sodium-containing fertilizers are used with calcium-containing materials like superphosphate, or in the presence of decaying green manure.

Conservation of Ca and Mg by some fertilizers. Fertilizers that contain calcium, magnesium, and sodium may aid materially in conserving the soil reserves of calcium and magnesium. In some soils conservation may be indicated by those changes in reaction toward alkalinity which result in a tendency to an increase in exchangeable calcium.

As regards sodium, it may conserve calcium and magnesium by acting as a protective agent. The composition of drainage waters from the Broadbalk Field at Rothamsted shows that nitrate of soda may cause no increase in loss of calcium and no appreciable increase in loss of magnesium by leaching, but that it may greatly increase the content of sodium in the drainage waters. Here soil analysis shows that sodium has effected a material reduction in the loss of carbonate of lime from the soil. Nitrate of soda has been found to effect conservation of calcium in the soil of the Wooster (Ohio) plots also. The sodium evidently neutralizes acids and

suffers loss by leaching, thereby saving the calcium and magnesium from attack. MacIntire and co-workers found that sodium nitrate was decidedly less active than magnesium and calcium nitrates in liberating, respectively, soil calcium and magnesium.

Effects of fertilizers on availability of elements. In addition to supplying plants directly with nutrient elements, applied fertilizers may materially affect, directly and indirectly, the availability of soil nitrogen, phosphorus, and potassium. Increased acidity to low pH values caused by acid-forming fertilizers may retard the decomposition and mineralization of soil organic matter, ammonification, and nitrification; and cellulose-rich materials may depress the formation of soil nitrates. Phosphates, on the other hand, may greatly accelerate the activity of azotobacters, the free-living nitrogen-fixing bacteria.

In his study of the effects of various nitrogen fertilizers on several different kinds of soils of humid regions, Fudge (1928) found that acid-forming fertilizers caused a marked decrease of available phosphorus and an increase of both water-soluble and available potassium, whereas basic fertilizers increased the availability of phosphorus, decreased the quantity of water-soluble potassium, but increased the quantity of *available* potassium (for plant growth), and also conserved the potentially available supply of potassium in soils. Working with sulphate of ammonia and nitrate of soda, Gracanin (Ger., 1930) obtained similar results, although he observed that the effects of the sulphate were not noticeable on extremely acid and alkaline soils. On some soils the effects were negative. He also observed that, in the results obtained with the nitrate, absorption of potassium by seedlings, in all cases, did not parallel the absorption of phosphorus.

Fertilizers and soil reserves of N, P, and K. Whether the use of fertilizing materials will ultimately result in increased supplies or higher "levels" of soil nitrogen, phosphorus, and potassium depends on several factors. Liberal application of phosphates usually increases the phosphorus reserves; but ordinarily, fertilizer practice is determined largely by meeting current needs of crops in accordance with the law of diminishing returns.

The effects of long and continual use of fertilizers on the soil supplies of nitrogen, phosphorus, and potassium may be typically shown by the results of a study of long-time soil-fertility plots of humid European countries by Christensen and Jensen (Den.,

1931). Their conclusions are as follows: (1) The nitrogen content of soils may be increased slightly by long and continual use of manure and by large applications of nitrate of soda. (2) Large quantities of nitrogen may be lost from soils by leaching. (3) Long and continual use of superphosphates results in a considerable accumulation of phosphorus which usually remains in soils in available forms. (4) Potassium usually does not accumulate in soils in any significant quantities through the use of potash fertilizing materials, and it suffers heavy losses by leaching.

Fertilizers and soil toxins. In many acid soils there exists a very close relation between acidity and active or harmful aluminum (see Index). Several investigators have concluded that the formation of aluminum sulphate in soils may be brought about through the use of acid-forming fertilizers, such as sulphate of ammonia. Superphosphate, on the other hand, precipitates toxic aluminum within plants and renders it inactive and hence non-injurious. That other fertilizing materials may produce favorable effects, so far as any soil toxins are concerned, is indicated by the results of some water-culture experiments conducted by Schreiner and Reed (1908), who found that sodium nitrate and calcium carbonate, respectively, aided materially in destroying toxic substances like vanillin and arbutin.

For effects of fertilizers on soil micro-organisms, see Chapter 19.

EFFECTS OF FERTILIZERS ON PLANTS

Fertilizers are used primarily to increase the growth of plants and the yield of crops. In addition to these principal effects, added materials may affect plants in different ways, in regard to nutrition, toxicity, character of growth, quality of produce, and plant diseases. Some of the more important effects are discussed, with a view to gaining a better understanding of the use and function of fertilizers.

Results of experiments have established two important facts: (1) Dilute solutions of single nutrient salts may prove to be toxic to plants; and (2) when two or more nutrient salts are mixed in solution (particularly if one is of calcium), there is a tendency for each to counteract the toxicity of the other, thus effecting a physiological or nutritive balance. The latter phenomenon, which is called "antagonism of ions," concerns the cations primarily. The tendency of nutrient salts to counteract the toxicity of each

other is called reciprocal antagonism. Calcium ions are most effective in antidoting other ions. Irrigated crops, until conditions grow worse, can tolerate salt concentrations above what would be toxic in single-salt solutions. A nutrient solution so constituted as to favor optimum growth is called a *balanced solution*.

Balanced fertilizers. The theory of so-called "balanced fertilizers" (mixed or complete) is based on physiologically balanced solutions, the idea being to supply crop plants with nitrogen, phosphorus, and potassium in proportions or ratios that will produce the best results. In practice, however, a great many soil and plant factors come into play, so that a balanced fertilizer, at best, can be approximated only theoretically.

Effects of combining fertilizer nutrients. When conditions call for the use of all three of the major fertilizing constituents, one should take into consideration the interaction and conjunct effects of the different elements.

Owing to the complex chemical nature of soils, a single-element fertilizer does not produce toxic effects as does a single nutrient salt in a culture solution. The common result is a certain increase in growth or yield with the separate addition of each fertilizing constituent. The quality of increase from each may be equal or widely different. On the addition of one element, there may be no increase at all. The total increase that may result from combining the three elements may be less than the sum of the single-constituent increases, it may be equal to their sum, or it may be greater than their sum. These effects are illustrated by the yields given in the tables on pp. 447 and 448.

The second of these tables gives a summary of results of a large number of tests which, on the basis of average increase in yield, show that the increases resulting from the use of three fertilizing materials (N, P, and K) were in most cases equal to or greater than the sum of the increases obtained when the materials were used singly.

The large increases in yields that result from combining the fertilizing elements indicate that each fertilizing material helps the other out. Retarded growth and reduced yields resulting from a lack of "balance" in mixed or incomplete fertilizers may be caused either by increased or by decreased absorption of the other elements present.

Conjunct Effects of Single-Element Fertilizer Materials

(Ohio Agr. Expt. Sta. Bull. 336, pp. 588-594)

Single-Element Fertilizers and Mixtures of Them	Crops Grown in 5-Year Rotation (25-Yr. Averages)						
	Indian Corn*		Oats	Wheat*		Clover Hay	Timothy Hay
	Quantity of Fertilizer Applied per Acre	Increase in Yield per Acre	Increase in Yield per Acre	Quantity of Fertilizer Applied per Acre	Increase in Yield per Acre	Increase in Yield per Acre	Increase in Yield per Acre
	Pounds	*Bushels*	*Bushels*	*Pounds*	*Bushels*	*Pounds*	*Pounds*
Nitrate of soda	160	5.42	4.57	120 †	1.85	381	373
Superphosphate (16-percent)	80	7.43	9.44	160	7.97	478	350
Sum of two yield increases	—	12.85	14.01	—	9.82	859	723
Mixture of nitrate and phosphate	240	14.47	16.37	280	13.75	1,143	820
Nitrate of soda	160	5.42	4.57	120 †	1.84	381	373
Muriate of potash	80	5.47	3.43	100	1.11	211	130
Sum of two yield increases	—	10.89	8.00	—	2.96	592	503
Mixture of nitrate and potash	240	7.58	6.45	220	2.72	416	334
Superphosphate	80	7.43	9.44	160	7.97	478	350
Muriate of potash	80	5.47	3.43	100	1.11	211	130
Sum of two yield increases	—	12.90	12.87	—	9.08	689	480
Mixture of phosphate and potash	160	15.42	13.03	260	9.31	941	571
Nitrate of soda	160	5.42	4.57	120 †	1.85	381	373
Superphosphate	80	7.43	9.44	160	7.97	478	350
Muriate of potash	80	5.47	3.43	100	1.11	211	130
Sum of three yield increases	—	18.32	17.44	—	10.93	1,070	853
Mixture of nitrate, phosphate, potash	320	19.30	19.32	380	16.58	1,379	996

* In addition, 50 pounds of dried blood were applied.
† Corn and wheat were fertilized; increases in yields of oats, clover, and timothy represent residual effects of fertilizers applied to corn and wheat.

Conjunct Effects of Single-Element Fertilizer Materials

Treatment	Crops, Number of Tests, and Average Increase per Acre											
	Corn (Maize)		Cotton		Hay		Oats		Potatoes		Wheat	
	Tests	Increase	Tests	Increase	Tests	Increase	Tests	Increase	Tests	Increase	Tests	Increase
		Bu.		*Lb.* *		*Lb.*		*Bu.*		*Bu.*		*Bu.*
Nitrate of soda (alone)	249	3.8	73	64	67	1,484	56	7.3	55	5.5	103	1.7
Superphosphate (alone)	405	3.4	181	69.8	82	660	81	3.6	82	18.8	192	3.5
Muriate of potash (alone)	289	6.3	36	34.5	38	84	60	1.6	64	16.1	114	0.4
Sum of increases	—	13.5	—	168.3	—	2,228	—	12.5	—	40.4	—	5.6
All three materials used	677	13.1	199	159.3	96	1,676	200	11.3	125	46.8	295	8.9
Sulphate of ammonia	52	0.9	—	—	13	1,367	8	11.7	6	-9.0	25	3.6
Superphosphate	405	3.4	—	—	82	660	81	3.6	82	18.8	192	3.5
Muriate of potash	289	6.3	—	—	38	84	60	1.6	64	16.1	114	0.4
Sum of increases	—	10.6	—	—	—	2,111	—	16.9	—	25.9	—	7.5
All three materials used	389	17.5	—	—	75	1,021	115	10.1	53	56.6	158	9.4
Nitrate of soda	249	3.8	73	64	—	—	—	—	—	—	—	—
Superphosphate	405	3.4	181	69.8	—	—	—	—	—	—	—	—
Kainite	84	4.9	161	32.3	—	—	—	—	—	—	—	—
Sum of increases	—	12.1	—	166.1	—	—	—	—	—	—	—	—
All three materials used	36	14.9	51	222.9	—	—	—	—	—	—	—	—

* Seed cotton.

Possible advantages of complete fertilizers. When crop requirements and soil conditions call for the application of nitrogen, phosphorus, and potassium, a complete fertilizer may offer a most important advantage in addition to the economies that may be effected in its use. Such a fertilizer may be compounded to have a neutral or alkaline effect on soils. Nitrogen, phosphorus, and potassium may be applied with economy in one application, and the mixture may be compounded to have a neutral or alkaline effect on soils; but to assure, under varied field conditions and for different crops, a physiological balance is quite beyond the range of possibilities. Furthermore, for some crops on certain soils—with potatoes on loams, for example—one application of a mixed or complete fertilizer may be sufficient to obtain satisfactory results; whereas for some other crops and soils—cotton on sandy soils, for example—application of phosphate, potash, and some nitrogen fertilizer before or at planting time, plus an application of quickly available nitrogen along one side of the row after the crop is up (side-dressing), may prove to be most productive.

Ratio of N, P, and K in fertilizers. Investigations of physiologically balanced culture solutions and of compound fertilizers have led to attempts to ascertain and to designate possible optimum ratios for N, P_2O_5, and K_2O of complete mixtures. But owing to incomplete knowledge and to the complexity of the problem, only approximations can be made. A comparatively few ratios may serve to meet ordinary practical needs in a given region or locality.

Indirect effects. Working on the problem of citrous decline in Arizona, McGeorge (1936, 1946) has found that high alkalinity creates an unfavorable physiological condition within the plants, which prevents proper utilization of manganese, iron, copper, and zinc. When the pH of these soils is lowered by acid-forming materials (sulphur, sulphur plus manure, sulphuric acid, and carbonic acids), thus making these soils similar in reaction to those of the trees' natural habitats, absorption of these elements is effected.

Fertilizer on poor v. on good soils. It would seem that crops would give greater responses to fertilizers on poor soils than on those of higher producing powers. Whether increases in yields may be larger on some soils than on others may depend on several factors—principally soil, fertilizer, and crop. Field results show that Indian corn, oats, and, to a lesser degree, wheat seem to re-

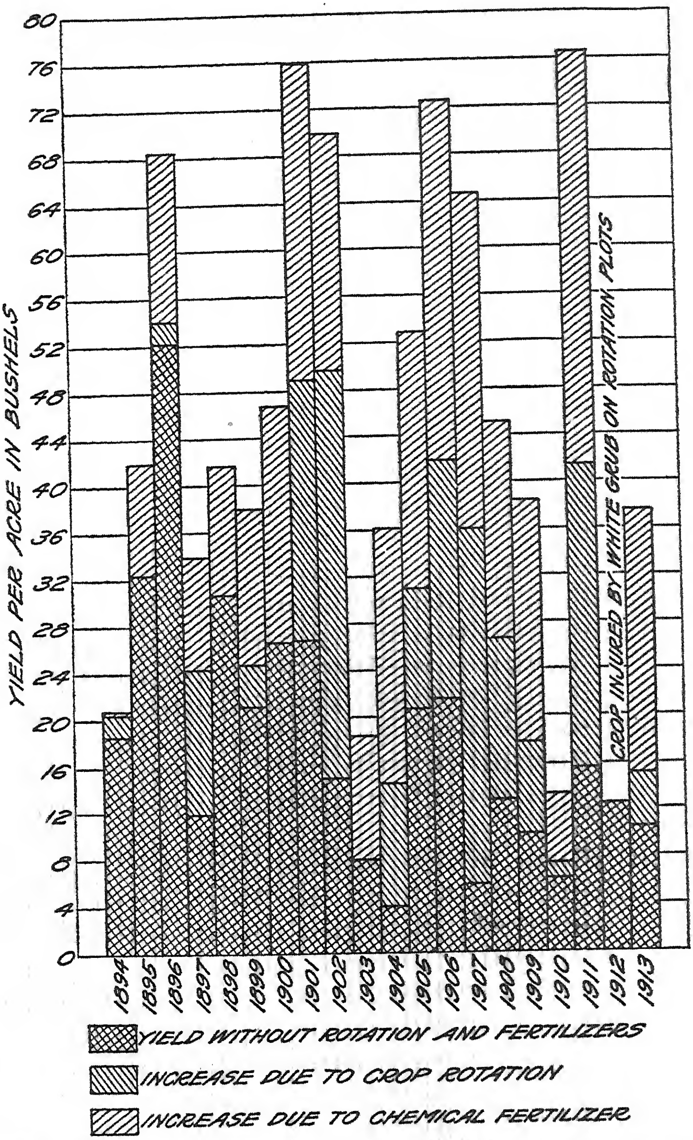

Fig. 100. Annual yields of Indian corn on plot 11 in rotation at Wooster, Ohio, showing how weather may increase or decrease the effectiveness of chemical fertilizer and crop rotation.

spond best to needed fertilizers on the poorer soils; whereas potatoes, cotton, and hay seem to give highest returns from fertilizers on the better soils.

Sodium as substitute for potassium. Whether sodium can be substituted for potassium in plant nutrition has long been a subject of controversy and investigation. From a study of this problem in field experiments, Hartwell and co-workers (1907-1919) have concluded that sodium can be substituted in part for potassium, particularly when the latter element is deficient. According to Heinrich (Ger., 1928), the sodium assumes a part of the function of potassium in the assimilating and conducting organs of plants, thereby allowing a greater part of the potassium to function in the seeds (Ch. 9). In addition to this substitution action of sodium, investigators have found that this element also makes soil potassium available, and that it tends to conserve soil calcium, magnesium, and potassium. Accordingly, sodium may aid materially in the nutrition of crop plants, particularly when the supply of available soil potassium is not sufficient for the requirements of crops, as has been shown by Holt and Volk (1945).

It is known that an application of common salt ($NaCl$) may cause increase in growth, presumably because of the beneficial effects of sodium. Orr (Eng., 1929) has suggested a deficiency of sodium in some soils, coupled with application of none, as a probable reason why natural pasturage in certain fields of the Romney Marshes of England does not fatten livestock.

Fertilizers and weather. The effects of weather on crop yields are well known. Meteorological conditions (temperature, precipitation, etc.) affect all the factors concerned in crop production, but not in the same manner nor to the same degree. In some seasons, weather may be of such character as to affect all factors favorably, whereas at other times it may affect all factors adversely. Again, the effects of weather on one factor may tend to increase yields; while on another factor the effects may be just the opposite. (In Fig. 100, note the effects of fertilizer and rotation in increasing the yields of Indian corn during 1896, 1903, and 1913; and in Fig. 101, note the effects of the same factors on yields of wheat for 1851, 1855, and 1859.)

Proper use of the right kind of fertilizer may partly make up for unfavorable effects of weather, as compared with yields without fertilizer. (See Fig. 100, fertilizer effects on yields of Indian corn

for 1904, 1909, and 1913.) Where fertilizer practice has been established, however, unfavorable weather may depress the effectiveness of fertilizers.

For crops planted somewhat later than usual, because of unfavorable weather or the necessity of controlling crop pests, such as European corn borer, fertilizer applied to increase the rate of

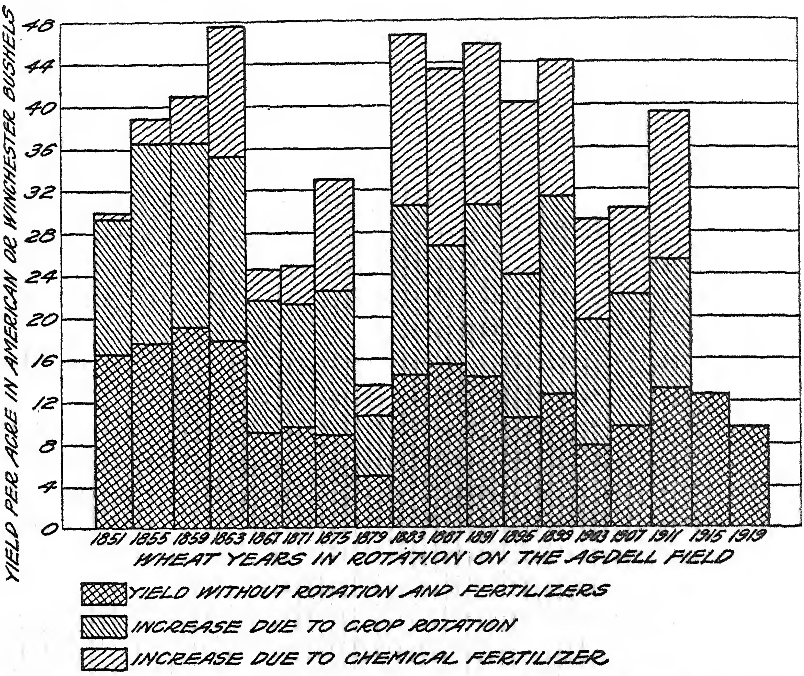

Fig. 101. Annual yields of wheat on rotation plot, 2-C, Agdell Field, Rothamsted, England, showing how weather may increase or decrease the effectiveness of chemical fertilizer and crop rotation.

growth may prove to be especially helpful. However, as most crops grow and yield best when planted at the proper time, but little can be expected of fertilizers in making up lost time if planting has been delayed too long.

Fertilizers are usually most effective when the supply of soil moisture is adequate for crop needs. In humid regions, an even distritution of adequate rainfall during the growing season is an important factor. Under subhumid and dry-farming conditions, use of fertilizers, particularly the nitrogen carriers, may reduce

yields, since the soil moisture may become exhausted through increased growth and greater leaf development (Ch. 12).

Nitrogen fertilizers not for growth only. Although nitrogen is noted for its effects in deepening the green color of leaves, increasing growth, and imparting tenderness to leaf products, it functions in a most important way in the development of fruit, grains, seeds, and fiber. Growth is also dependent on elements other than nitrogen, for the reason that the effectiveness of one element in plant nutrition is dependent on another or others.

In fertilizer practice, particularly in orchards and in the production of Indian corn, cotton, and potatoes, nitrogen is a most important factor in increasing yields. So far as nitrogen is concerned, fruitfulness of most crop plants is associated not with the quantity of available nitrogen, though quantity is important, but with a condition of balance between carbohydrates and nitrogen within the plants (Ch. 20).

Nitrogen aids in formation of fruit buds. Of the major fertilizing elements, nitrogen is the most important nutrient that affects the "setting" and development of fruit. According to MacDaniels and Heinicke (1930), a deficiency of this element in the tissue of a tree may be the cause of a heavy drop of young fruit, owing to keen competition by vigorous shoots and rapidly expanding leaves and flowers for water and for a limited supply of nitrogen. Part of the nitrogen required may be stored in the bark of roots, in the trunk, and in the branches near the buds; but commonly a large part must be directly supplied. Available nitrogen applied about 4 or 6 weeks before blossoming time is usually very effective in supplying the young fruit with adequate nitrogen in the face of keen competition with shoots and leaves. For orchards in sod, applications of readily available nitrogen commonly give striking results in increasing the set of fruit, vegetative growth, and yields.

Fertilizers increase nitrogen content of crops. That the nitrogen content of crops and their produce can be increased through the use of nitrogen fertilizers has been established. The increased nitrogen in the plant occurs in organic forms. Notwithstanding the general and comparatively generous utilization of nitrates by agricultural plants, comparatively small quantities of nitrate, under normal conditions, are to be found in plant tissues. Products of crops that benefit from an increased nitrogen content usu-

ally have higher quality and greater food value than products of unfertilized crops.

With cereal crops, an adequate supply of available nitrogen results in increased growth and yields, higher percentage content of nitrogen in the grains, and higher-quality produce. Soil is commonly an important factor. For example, in the border zone between forest and prairie soils of the Middle West, farmers and operators of grain elevators have long recognized the superiority of brown forest silt loams (*Miami* series) for growing wheat, as compared with prairie silt loams (*Carrington* series), the superiority being indicated by the ability of the grain to stand up, by higher-quality grain and straw, and by greater weight per unit volume.

On root crops, nitrogen fertilizers produce effects similar to those produced on cereals. Excessive nitrogen, however, may reduce the percentage of dry matter in the roots and decrease the percentage of sugar in beets and of starch in potatoes.

Pasture grasses commonly respond to nitrogen fertilizers by increasing leaf growth and protein content, and thus increasing the feeding value of the pasturage.

Much available nitrogen commonly delays maturity of crops. Furthermore, Prianischnikov (Russ., 1927) and subsequent investigators have found that a green plant may be injured by an excess of ammonic nitrogen when once it ceases to manufacture corresponding quantities of carbohydrates. In this respect plant cells differ from animal cells, in that the latter can excrete excess nitrogen as urea.

Normally, the more nitrogen a plant absorbs, within certain limits, the more protein and other complex substances are formed, with increase in development of leaves, manufacture of carbohydrates, transpiration of water, and absorption of mineral nutrients. So long as these changes remain balanced or compensate each other, with limited quantities of nitrogen, the result is a larger plant similar in composition to the original or smaller one. But unbalanced conditions of growth may result in excessive production of carbohydrates, with relative decrease in nitrogen. On the other hand, absorption of much nitrogen, particularly in the nitrate form and during latter stages of vegetable growth, may not be balanced by corresponding quantities of carbohydrates. Under

such conditions, much of the nitrogen may remain as excess, usually in the form of plant storage products.

Nitrogen and protein content of wheat. The protein content of wheat usually increases with increase in the quantity of available nitrogen. When nitrogen fertilizers are applied during early growth, the effects are increased growth and yield. But when quickly available nitrogen, as in the nitrate form, is applied when the grain heads are forming, according to results obtained by Davidson and LeClerc (1917) and other investigators, the effect may be an appreciable increase in the protein and gluten contents of the grain. This increase improves the baking quality of the flour.

It has been suggested that in order to increase both yield and protein content of wheat, the crop should be fertilized with nitrogen during early growth and also at heading time. But when farmers receive no premium for high-protein wheat, the more profitable fertilizer practice is to fertilize this crop for increased yields only.

Nitrogen and preservation of fruit. Fruit growers have been puzzled regarding the effect of nitrogen fertilizers on the keeping quality of fruit. Apples and peaches that have been grown with a liberal use of quickly available nitrogen have been investigated in storage, and it has been found that although the fruit may not be highly colored, owing to increased foliage, neither internal breakdown nor softening during storage takes place to any appreciable degree. Investigations of the shipping and keeping qualities of fruits like tomatoes and strawberries have given similar results. Wallace (Eng., 1930) has found that the condition of fruit trees regarding nutrition markedly affected the keeping quality of the fruit and the flavor of the cider made from the fruit.

In fertilizing fruit trees, and other crops as well, one should recognize that applied nitrogen, phosphorus, and potassium are not foreign or substitute elements, but rather natural and essential nutrients; normal growth and development of plants should result from rational use of proper fertilizers in any well-regulated system of cropping. Excessive quantities, particularly of nitrogen and other concentrated salts, should be avoided.

Lodging in small grains. Small grains commonly fall partly or completely over, sometimes flat on the ground, as a result of factors

other than violent winds, heavy rains, and hail storms. Common characteristics of growing grains that "lodge" or break down are much growth of stem, increased leaf development, and weak straw due to shading by much leaf growth or thick planting.

From their study of lodging in oats and wheat, Welton and Morris (1931) have concluded that grains go down as the result of the interaction of many environmental (soil, weather, etc.) and hereditary factors. Lodging occurs when the resultant of these factors is a comparatively low content of dry matter per unit length of culm or straw. Such stems may result indirectly from a low carbohydrate-nitrogen ratio within the plants or directly from a thick stand.

A low carbohydrate-nitrogen ratio usually results from excessive available nitrogen which favors rank growth of straw and leaves. Increased shading resulting from this rank growth favors the development of succulent and weak stems, which cannot stand up or stand the strain of wind, especially when the heads are heavy with drops of rain water. Thus the stems kink badly or abruptly bend near the bottom below the leaves. When beaten down, such grains do not stand up again. This leads to undeveloped kernels, loss of grain, and to smothering of grass and clover seedings.

Control of lodging lies in withholding nitrogen fertilizers, depressing nitrification by disking land rather than plowing it, fall plowing (see Index), and planting varieties of grains that have short and stiff straw.

Nitrogen and plant diseases. Utilization of much nitrogen by plants commonly results in the development of soft and sappy leaves which are susceptible to attacks of insects and certain diseases, probably because of thin-walled tissues or changes in structure or composition. Wheat may become susceptible to rust; tomatoes, to "stripe" disease (bacterial) and blossom-end rot (not parasitic); and potatoes, to blight (*Phytophthora*).

Some plant diseases are malnutrition disturbances which result from a deficiency of nitrogen. In some instances the leaves become yellowish in color, as may be commonly observed in poorly cared-for orchards and in corn (maize) and grain fields where the soils are deficient in nitrogen.

Increasing the vigor of plants through the use of nitrogen, together with mineral elements, if needed, may have the same effect in increasing resistance to certain diseases and parasites in plants as proper feeding does in animals. This may be typically illus-

trated in the effects of readily available nitrogen and phosphorus in reducing the loss from root rot, in increasing growth, advancing maturity, and in increasing the yields of cotton, as on heavy, black-land prairie soils of Texas.

Phosphates favor root development. Applied phosphorus produces its first effects on the roots of young plants by increasing their growth, as compared with plants that lack this element. This means the development of more extensive absorbing systems. This development is most significant in that plants become firmly established in soils during early stages of growth. This stimulating effect on roots is soon followed by more rapid development of leaves, shoots, and kernels or ears.

Phosphates effect early maturity. On soils deficient in available phosphorus, the use of phosphate fertilizers tends to favor early maturity of crops. On some soils, crops fertilized with phosphates may ripen from 5 to 10 and more days earlier than unfertilized plants.

The maturing of crops cannot be regarded as a primary function of phosphorus any more than making plants grow can be regarded as the primary function of nitrogen. The presence of adequate phosphorus, together with other essential elements, favors plant growth and development; thus less time is required for plants to come to the fruition stage. Phosphorus has long been regarded as functioning principally in seed development; but from a study of tomato plants, MacGillivray (1925) has found more phosphorus in the nonseed part of the fruit than in the seeds, regardless of maturity or use of phosphates.

Because of the effects of phosphorus in hastening maturity of crops, the use of phosphates is especially advantageous during hot and dry and wet and cold seasons; in growing Indian corn; and for crops that are particularly responsive to phosphate treatment, including turnips, potatoes, cereals, and sugar beets.

Added phosphorus does not necessarily alter the composition of plants. In proportion to the increase in growth made, the phosphorus content may remain the same. Nevertheless, the phosphorus content of crop plants may be materially increased, through liberal applications of phosphates, in much the same way that the calcium and magnesium contents of herbage and other crops may be increased by adding agricultural lime to strongly acid soils.[3]

[3] BLAIR, A. W., and PRINCE, A. L. THE INFLUENCE OF PHOSPHATES ON THE PHOSPHORIC ACID CONTENT OF THE PLANT. Jour. Agr. Res. (U.S.), Vol. 44, No. 7, p. 579. 1932.

Phosphates improve quality of produce. Among the most noticeable effects of phosphorus on the quality of the crop are well-filled kernels and increased weight of grain per unit volume. The beneficial effects of phosphorus on quality of produce may be appreciated the more when one observes the stunted growth and "deficiency diseases" of plants growing on phosphorus-deficient soils, and when one observes the fact that certain malnutrition diseases develop in animals when they feed on phosphorus-poor forage.

According to Hart and co-workers (1927), a peculiar disease, called "pica" by veterinarians, which has affected some dairy cows of northeastern Wisconsin, may probably be caused by low-phosphorus roughages and pasturage. Theiler and colleagues (S. Af., 1924) have also described phosphorus-deficiency diseases of animals fed on phosphorus-starved forage. Similar effects on livestock have been observed in Montana, Minnesota, Australia, New Zealand, Norway, and Germany.

Potash fertilizers, effects on crops. Through the aid of potassium, plants are able to manufacture sugars, starches, and celluloses out of carbon dioxide and water by means of chlorophyll, cell protoplasm, and the energy of sunlight. Although potassium does not enter into the composition of the carbohydrates, when potassium is withheld the manufacturing processes cease. Accordingly, adequate supplies of this element are required especially by corn (maize), potatoes, sugar beets, mangels, wheat, oats, barley, and clover. For symptoms of potassium deficiency in plants, see Chapter 26.

Potash fertilizers seem to enable plants to withstand dry conditions better, probably by facilitating the moisture supply or enabling the leaves to function longer. Grasses well supplied with potassium remain green longer under dry conditions, as compared with plants that lack potassium, which soon wilt and turn brown.

Excessive potassium may prolong vegetable growth, and hence delay maturity. With some plants like cotton, where several pickings are necessary, liberal fertilization with potash salts may prove to be advantageous. Higher plants may absorb liberal quantities of potassium, commonly more than is normally required. Potassium tends to accumulate in the leaves and stems. Much of this potassium may be washed out by rain water or may return to the soil through the roots, as various investigators have shown.

Potash fertilizers improve quality. Potassium favors ripening of cereals, tends to increase the weight of grains, tends to lower the content of nitrogen in barley (thereby improving its malting qualities), enhances cooking qualities in potatoes, improves quality in tobaccos, and, in general, develops resistance to fungous diseases.

Potassium and nitrogen relations. In plant nutrition, the functions of nitrogen are dependent to a large degree on potassium; and conversely, the functions of potassium are dependent largely on nitrogen. Thus, in fertilizing crops, this close relationship between potassium and nitrogen should be kept in mind. Unproductive currant bushes growing on a nitrogen-rich soil have been made fruitful, and peonies on a potassium-deficient soil have been made to bloom on the correction of unbalanced potassium-nitrogen relations. Bronzing of leaves of young orange and apple trees and of potato leaves has been attributed to insufficient supplies of potassium or to an excess of nitrogen with a minimum supply of potassium. In New Jersey, Schermerhorn (1929) has found that the production of high yields of sweetpotatoes of desirable chunky shape depends on a certain relationship between available potassium and nitrogen. Martin and colleagues (1931), working with potatoes, have obtained the largest total yields of tubers from the use of fertilizer mixtures that carried from medium to high quantities of potassium and nitrogen.

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REVIEW QUESTIONS

1. What is the true meaning of the term "physiologically acid," as applied to fertilizer salts? "Physiologically basic"?
2. What effects do chemical fertilizers and different manures have on soil reaction? Give examples.
3. A gardener has succeeded in adjusting the reaction of his soils for maximum yields of the crops he grows, and he irrigates (overhead) with hard water. How should he fertilize for sustained yields? Explain.
4. Explain how the use of nitrate of soda may conserve soil calcium and magnesium.
5. What are the facts regarding the loss of nitrogen, phosphorus, and potassium through the use of fertilizers?
6. Illustrate the conjunct effects of single-element fertilizers. What significance have these facts physiologically and economically?
7. Compare the carbohydrate-nitrogen relationship in crop plants with the potassium-nitrogen relationship.
8. Is nitrogen to be regarded as the growth element? Discuss.
9. Is it possible to increase the percentage of N, P, and K in plants through the use of fertilizers? Illustrate.
10. In regard to the effects of fertilizers on soils and crops, with what, after all, are users of fertilizers most concerned?

CHAPTER 23

FERTILIZING PLANTS TO MEET THEIR NUTRIENT REQUIREMENTS

It is becoming recognized that fertilizers are used to supply plants, through soil mediums, with essential and available elements in order to meet their nutrient requirements. Proper fertilizer practices are based on these two scientific facts: (1) that plants are the objects fertilized; and (2) that soils, into which the absorbing systems of plants extend, hold the applied nutrients while they are being utilized by the plants. In modern fertilizer practice, therefore, the first consideration is for the plants or crops, and the second, for the soils; that is, the proper use of fertilizers involves plant factors, on the one hand, and soil factors, on the other.

The plant factors include the following: (1) the kind of plants to be fertilized; (2) their habits of growth; (3) nutrient requirements (total and at different stages of growth); and (4) physiological conditions that affect the absorption and assimilation of the nutrient elements. Among the soil factors may be named these: (1) tilth; (2) soil water; (3) aëration; (4) soil reaction; (5) organic matter; (6) micro-organisms; (7) content of available nutrients; and (8) soil leaching. These two groups of factors are interactive, and they are influenced more or less by climate, weather, kind of fertilizer, method of fertilization, and crop rotation.

Limitations of fertilizers. Valuable as fertilizers are, there are certain limitations to what can be accomplished by them, even though scientifically used. Although deficiency or lack of available nutrients is a common cause of poor crops or infertility, it does not follow that fertilizers alone can restore or effect soil productivity. In order to obtain the best results from fertilizers, one should take into consideration not only all the plant and soil factors involved in their proper use, but also climate, weather, kind of fertilizer, method of fertilization, and crop rotation.

Choice of nitrogen fertilizers. For the best results, the fertilizer used must be the right one in relation to soil conditions and the needs of the crop concerned. If a soil contains adequate calcium and magnesium, acid-forming nitrogen fertilizers may be used with as good results as other forms of nitrogen; whereas on strongly acid soils, basic fertilizers may prove to be the most beneficial.

Some plants grow best with nitrate nitrogen, whereas others grow best when they are supplied with some ammonium nitrogen during early growth. Some plants require the nitrate form throughout the growing period.

For quick results and for use under unfavorable weather conditions, as in early spring, nitrates are usually most effective in promoting growth. Nitrates are necessary also for fast growing vegetables. A common theory calls for providing a crop with a continuous supply of nitrogen by using a mixture containing nitrate, ammonium salts, and organic materials. Several investigators have found that mixtures of different sources of nitrogen may be more effective and economical for certain crops than a single source.

When fertilizers are applied in one application under conditions of considerable rainfall, particularly on sandy soils, the advantage lies with ammonium salts, organic fertilizers, and other compounds which, like urea, give rise to ammonium ions. It is also advantageous to use ammonium salts in growing paddy rice, in order to avoid loss of nitrogen through denitrification. On the other hand, nitrates may be used for best results under conditions of limited rainfall or scant water supply and on poorly drained soils, where nitrification and mineralization of organic matter may be very slow.

Where potatoes are susceptible to scab disease (*Actinomyces scabies*), the choice of fertilizer or its composition may be determined largely by the degree of soil acidity that is required to control the scab (Ch. 15).

Under alkali-soil conditions, and on clay soils that puddle easily, the single use of sodium-containing materials may not be advisable (Ch. 4). On alkali soils, acid-forming fertilizer like sulphate of ammonia may be preferred.

Fertilizers that give rise to free ammonia when applied on sandy soils call for an ammonia-calcium balance in the zone of germinating seeds and of seedlings, in order to prevent injury; otherwise

such fertilizers should be avoided (Ch. 19). When a fertilizer gives rise to toxic compounds as the result of uneven distribution, as with Cyanamid, the fertilizer may be safely used if attention is given to the time of application (Ch. 21).

Choice of phosphate and potash fertilizers. The choice of phosphate fertilizers depends largely on the availability of the phosphorus. Superphosphates are commonly used for immediate results. Under certain soil conditions and for economy, rock phosphate may be used. On irrigated soils of arid and semidesert regions, the use of ammonium phosphate is advisable in order to supply extra nitrogen to "balance" the phosphorus.

The choice of potash fertilizers, all of which are water-soluble, is commonly based on economy and a knowledge of the effects produced on the crops concerned. With tobacco, the chlorine and magnesium contents of these fertilizers are important factors. On alkali soils of humid regions (developed under conditions of ground-water effects), potash fertilizers may prove to be beneficial in establishing physiological balance between potassium and nitrogen.

Commonly, soil deficiencies determine whether phosphates or potash fertilizers should be used singly or together, or whether all three elements—nitrogen, phosphorus, and potassium—should be applied. When conditions call for complete mixtures, the choice of "analyses" may involve proper ratios of N, P_2O_5, and K_2O.

Economy is usually an important factor affecting the choice of fertilizers, both in regard to purchase price and net returns. Consumers should also give due consideration to the permanent effects that fertilizers might have on the productivity of their soils.

Methods of applying fertilizers. The fact that the absorbing systems of crop plants, so far as nutrient elements are concerned, develop mainly in the upper, tillable part of soils allows for several different methods of applying fertilizers. Manures may be turned under; manures and commercial fertilizers may be broadcast and then incorporated into the seed bed by harrowing; commercial fertilizers may be applied in drillrows and covered, or they may be broadcast as top-dressing, dissolved and applied as solutions, applied as side-dressing, or applied in irrigation water; in the case of shade trees, the fertilizer is commonly placed in holes that are punched into the ground around the trees. In fertilizing some

crops, two or more methods may be used, as may be determined by kind of fertilizer and special needs.

Plowing under manures affords several advantages. When properly done, litter is covered, coarse materials are placed where they can decompose readily, and the fertilizing constituents are uniformly distributed throughout the seed bed in between the furrow slices, all of which tend to develop conditions favorable for plant growth. The heavier-textured soils are particularly benefited thereby (Ch. 11).

Green manures are usually turned under. Rock phosphate is sometimes applied with barnyard manures and green manures.

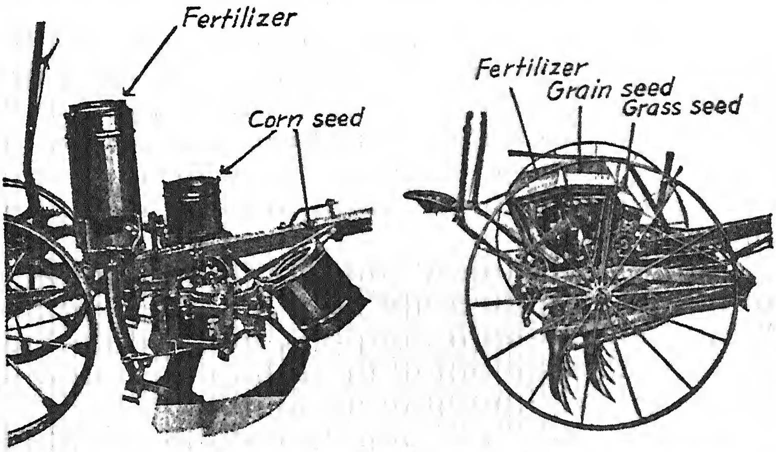

Fig. 102. Farm implements equipped with fertilizer attachments: left, corn (maize) planter; right, small-grain drill.

Disking in manure is a common practice on sandy and loamy soils (Ch. 21), and for wheat. When thus applied, manure should be composted and be comparatively free from litter or trash. Broadcasting commercial fertilizers and then mixing them into the seed bed by harrowing effects even distribution and, when very heavy applications are made, eliminates danger of injury by "burning."

Drillrow and hill applications of fertilizers have proved to be economical, profitable, and scientifically sound. This method consists in placing fertilizers in the drillrows or hills of intertilled crops usually at planting time by means of implements or fertilizer attachments on planters and grain drills (Fig. 102). The fertilizer

may also be applied in drillrows and mixed with the soil material previous to planting. In this latter manner, rather heavy applications may be made without any appreciable injury to the plants. Placing fertilizers that carry phosphorus and potassium, elements that are readily fixed in soils, in the zone of root development may result in increased effectiveness.

Care should be taken not to allow much fertilizer salts to drop on the seeds; otherwise germination may be greatly delayed or

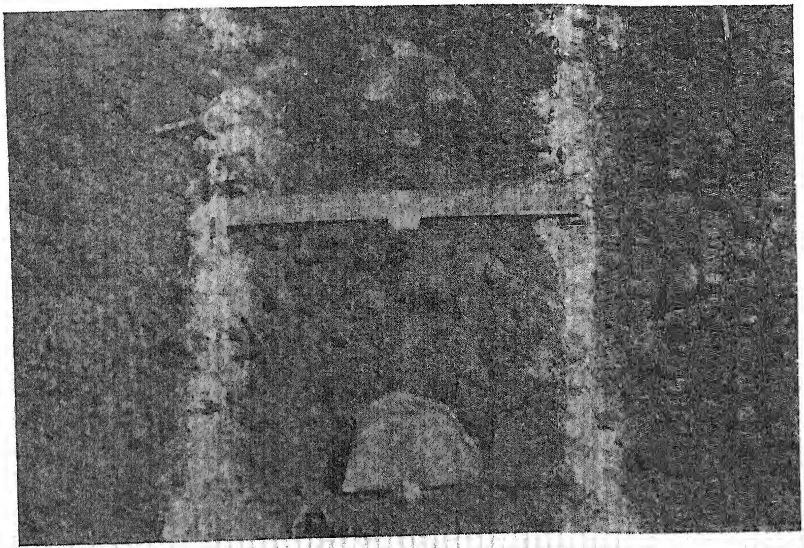

Fig. 103. Ideal placement of chemical fertilizer in the drillrow for potatoes. The fertilizer is placed on both sides of the seed pieces and is separated from them by at least a 2-inch layer of soil material. The fertilizer may be placed level with or about 2 inches below the level of the seeds.

entirely prevented. For best results, fertilizers should be placed on both sides of the seeds, at about the same level or slightly lower, and as near as possible to the seeds without causing injury. For maize, the horizontal distance between seed and fertilizer should be between ½ and ¾ inch. The placement of fertilizers in drillrows for potatoes is shown in Figure 103. Drilling fertilizers for small grains through the use of ordinary grain drills at planting time is usually more effective than broadcasting or drilling in a separate operation.

Some seeds—including field peas, cowpeas, navy beans, and soy-

beans—are very sensitive to contact with fertilizer salts. In the drillrow and hill methods of application, drillability of fertilizer is an important factor affecting distribution.

Top-dressing consists in broadcasting manure or commercial fertilizer over the surface of any cropped land. Here the effectiveness of a fertilizer depends on solubility of the fertilizing compounds and on rain or artificially applied water to carry the nutrients down to the absorbing roots. Wheat and other small grains, hay, pasture grasses, and turf grasses are commonly fertilized in this manner.

On golf greens and lawns, all-soluble fertilizers are commonly applied in solution.

Side-dressing consists in applying easily soluble fertilizers, particularly nitrates, along one side of the rows of intertilled crops after the plants are up. The great advantage of this method lies in the opportunity it affords to supply emergency needs of crops for nitrogen, and to apply nitrogen with the minimum loss and for most economical returns on leachy soils in regions of abundant and heavy rainfall.

Fertilizing by irrigation, that is, introducing water-soluble fertilizers into irrigation water for distribution, has been practiced for some time. The principal advantages are: (1) combining of irrigation and distribution of plant nutrients into one operation; (2) making possible uniform distribution of small quantities of fertilizer over large areas; (3) effecting economy in the case of crops that are benefited by frequent applications of small quantities of fertilizer; and (4) making possible deeper penetration of soluble phosphates into the root zone.

Fertilizing large shade trees is usually accomplished by injecting fertilizers into the ground under the outer branches. The holes are made by means of a crowbar or some other suitable tool. In this manner soluble phosphorus compounds and potassium salts can be placed within easy reach of the roots. Soluble nitrogen fertilizers are usually broadcast around the trees.

Fractional application of fertilizers. There are certain advantages to be gained in fertilizing some crop plants, such as cotton, at different stages of growth. This holds particularly true with respect to nitrogen. From one fourth to one half of the total quantity used for a crop may be applied with phosphate and potash before or at planting time, and the remaining quantity may

be applied at such time after the crop is up or at different stages of growth to best meet the needs of the crop, and at the same time to effect the greatest economy in the use of fertilizer nitrogen. This method of treatment is called "fractional application" and "split application" of fertilizer.

On sandy soils, fractional application of nitrates may greatly reduce the loss of nitrogen by leaching. Moreover, applying most of the nitrogen as side-dressing reduces the concentration of salts at planting time. Profitable use of concentrated fertilizers and of heavier applications of ordinary fertilizers for some crops (tobacco and cotton, for example) may be made possible through fractional application of nitrogen.

Profitable v. maximum yields. Maximum yields on a given soil can be produced only when all factors favor to the highest degree the growth of high-yielding varieties of crop plants. When the water supply is adequate throughout the growing season, most liberal applications of manure and fertilizers are usually required to produce the highest possible yields. Producing such crops may not only be unprofitable, but also be most wasteful of nutrient elements. Fertilizer practice is based on profitable crops in accord with the law of diminishing returns, rather than on maximum yields (see Index).

The quantity of fertilizer that may be used for a given crop on a given soil is usually determined in accordance with normal conditions and the law of diminishing returns. For example, under the favorable normal soil and climatic conditions of Aroostook County, Maine, potatoes are fertilized with as much as from 2,000 to 3,000 pounds per acre of complete mixtures like 4–8–8 and 5–8–7.

Charging cost of fertilizer against crops. In a well-managed and economical system of cropping, when several different crops are grown in rotation, only the most responsive or profitable crops are fertilized, and the other crops that follow profit by residual fertilizer effects. In cost accounting, the fertilizer used is charged against all the crops of the rotation according to benefits received. According to Salter (1926), in Ohio rotations of (1) Indian corn, (2) oats or soybeans, (3) wheat, (4) clover, and (1) maize, (2) wheat, (3) clover, (4) timothy, about two thirds of the benefits from fertilizing wheat is realized in increased yields of that crop. He found that wheat received 67 percent of the benefits from su-

perphosphate, 68 percent from potash fertilizer, and 71 percent from nitrate of soda.

In general, about 40 percent of the value of fertilizer is realized in the crop the first year, 30 percent the second year, 20 percent the third, and 10 percent the fourth.

FERTILIZING CROPS

No definite rules can be given for fertilizing crops that can be grown under a wide range of conditions; but there are certain facts and fundamentals that may aid in working out successful fertilizer practices. Some of these facts and fundamentals will be briefly discussed in their relation to different kinds and types of crops.

CEREALS

Barley (*Hordeum sativum*). The barley regions of the United States have climates varying from somewhat subhumid to semi-arid, with much sunshine. The temperature range of this crop is wider than that of any other cereal. Barley excels wheat in drought resistance. In California it matures in districts where the average annual rainfall is 10 inches. It cannot endure much wet weather nor wet soils.

This crop can be grown profitably on less productive soils than can wheat. As compared with oats, it requires more nutrients per bushel, its roots do not penetrate so deeply into soils, and it matures in less time. Inasmuch as barley must obtain its greater quantity of nutrients from less soil area and in less time than oats, it requires richer soils. Barley is rather sensitive to soil acidity (Ch. 15), which probably explains, in part, the fact that it grows better than any of the other small grains on alkali soils. In general, best soils for barley are rather fertile, well-drained loams.

Several investigators have studied the nutrition of barley, and results seem to show that this crop requires an adequate supply of available nutrients during the first half of the growth cycle, and that this is the most important requirement to be met in order to obtain best results.

In regard to the best form of nitrogen for barley, Nehring (Ger., 1929-1934) found that when the reactions of the mediums fell below pH 5.5, nitrates proved to be better sources of nitrogen than ammonium salts; on neutral soils there was but little differ-

ence in the two forms of nitrogen; and on alkaline soils nitrate gave low yields.

Barley is commonly grown after crops like potatoes and other root crops that receive manure, commercial fertilizer, or phosphate only; therefore, it is usually not necessary to apply more fertilizer. Phosphorus, potassium, and some nitrogen may be applied for winter barley at seeding time, and most of the nitrogen may preferably be applied as top-dressing when growth starts in the spring.

With spring-sown barley, the fertilizer is applied at seeding time. Rate of application may vary from 100 to 150 pounds per acre of nitrogen fertilizer, from 200 to 400 pounds of superphosphate (16-percent or equivalent in some other form), and from 50 to 100 pounds of potash fertilizer. A complete fertilizer, analyzing about 2–12–4 or 4–12–4, may be used on unmanured land, whereas on manured land only phosphate may be needed.

Corn (maize), *Zea mays.* The largest acreage of maize is grown in regions that have at least 20 inches of average annual rainfall, with a marked summer maximum, and whose summer temperature averages about 75° F. This crop does not thrive in regions of cool, cloudy summers. It does best in warm (not hot) humid climates, with frequent rains, and much sunshine.

Maize may be grown on sandy lands, clayey soils, and peat; and although it can tolerate a wide range of soil reactions, it should not be grown on alkali soils. Best corn soils are well-drained, deep, warm loams which contain considerable quantities of organic matter and available nitrogen. Water is commonly a limiting factor, particularly during the critical period of ear formation.

This crop requires liberal quantities of nutrients, particularly during the earlier stages of growth. Duley and Miller (1921) found that optimum supplies of nutrients during the third 30-day period largely determined ear production; although when there was an ample supply of mineral elements at the end of the second 30-day period, the leaves and stalks contained sufficient material for the production of fairly good ears.

In regard to utilization of ammonic and nitric nitrogen, Dikkussur (Ger., 1930) and Loo (Jap., 1931) have found that ammonic nitrogen (NH_4) can be readily absorbed by maize plants when the acidity of the mediums is brought to a pH value of about 7, whereas nitric nitrogen (NO_3) can be absorbed better in weak acid solutions. Pirschle (Ger., 1931) has obtained results showing

that, in constantly renewed cultures, nitrate and ammonium forms of nitrogen may give equally good growth in slightly acid mediums. Ammonium nitrogen may prove to be better in alkaline and nitrate in strongly acid mediums. Some investigators have found that maize plants may respond best to mixtures of these two forms of nitrogen.

Being strong "feeders," maize plants can make use of coarse manure, and can grow on soddy land better than most other crops. Thus, manure is a common fertilizer used, and it usually follows sod crops, such as hay and clover, in rotation.

When manure is used or when the crop is grown on bottom-land soils, from 200 to 500 pounds of superphosphate (16-percent) per acre may be all the additional fertilizer required. If the crop indicates the need for additional nitrogen, the same may be supplied by from 100 to 200 pounds of nitrate or ammonium salts, applied as side-dressing when the plants are about 12 inches high (North) or knee-high (South). When maize follows well-fertilized cotton, usually only nitrogen is needed, which may be supplied by from 100 to 200 pounds per acre of quickly soluble nitrogen fertilizer, applied as side-dressing.[1]

Applying a suitable complete fertilizer like a 2(N)–12–4 or a 2–12–6 properly in drillrows at the rate of 400 pounds an acre may give better results than 500 or 800 pounds applied broadcast. For application in hills, when properly placed, from 125 to 200 pounds per acre of a similar mixture may be used. Under favorable conditions, sulphate of ammonia may prove to be a somewhat superior source of nitrogen, or a mixture or compound containing both nitrate and ammonium forms of nitrogen.

Oats (*Avena sativa*), a cool-weather crop, are unprofitable in regions of high temperature, except when abundant water is available. The world distribution of this crop is but little affected by soils. It can be grown on soils that vary widely in reaction, up to that of medium-grade alkali land. Being a "strong feeder," it may yield well on rather poor soils, provided the water supply is adequate. The best soils for oats, however, are those that allow early seeding in the spring so that the crop may mature before hot weather sets in.

Oats are commonly grown after manured or fertilized crops; and as they are benefited by residual effects of fertilizers, they

[1] WILLIAMSON, J. T., APPLETON, W. H., and HELMS, H. B. FERTILIZING EXPERIMENTS WITH CORN. Ala. Agr. Expt. Sta. Circ. 52. 1927.

usually do not receive any additional treatment. On the better soils, oats are apt to lodge (see Index).

Oat plants in water cultures have been found to absorb ammonic nitrogen more readily than nitric nitrogen during the first half of the life cycle, and to reverse the process during the second half (Fig. 95). Under field conditions, however, responses of this crop in different countries indicate that, of single materials, nitrates are commonly more effective on this crop than ammonium salts, soil acidity being an important factor. Pirschle (Ger., 1931) found that (in cultures) oats and other crops that can utilize ammonic nitrogen, especially during earlier growth, responded best to mixtures containing both ammonic and nitric nitrogen, as compared with single-element materials.

For winter oats on unmanured and poor soils, from 200 to 400 pounds of muriate of potash, or equivalents in mixtures, may be applied at planting time; and from 75 to 150 pounds of readily soluble nitrogen fertilizer may be applied as top-dressing when growth starts in the spring. For spring-sown oats on similar soils, from 400 to 600 pounds of a mixture analyzing about 2 or 3 percent N, 12 percent P_2O_5, and 4 percent K_2O may be applied at seeding time.

Rice (*Oryza sativa*). Although a tropical cereal, rice is successfully grown in temperate regions having average annual temperatures above 75° F. during 4 months of the growing season. Paddy or "swamp" rice requires flooding at frequent intervals, and grows best in a damp climate. This crop may be grown on rather widely different soils, but most favorable conditions include friable loam underlain by heavy clay, to prevent underdrainage and to hold the water that is so essential in rice culture.

On some soils, rice may respond to phosphate and potash treatments and to sulphate of potash (100-pound applications). In some places, best yields have been obtained when the crop is grown in rotation with legumes, and when green manure is used. Bartholomew (1929), Gericke (1930), and Pirschle (Ger., 1931), have found that ammonic nitrogen is not required by rice plants for normal growth under controlled conditions; but owing to cultural conditions and low absorptive power of the plants for iron, the common nitrogen fertilizers used for paddy rice is sulphate of ammonia, applied at the rate of 100 or more pounds per acre.

Rye (*Secale cereale*). The fact that rye produces satisfactory yields under conditions of severe winter temperature, poor soils, and on rough and hilly land is well known. Although it is the best successor to other small grains on poor lands, it thrives best on fertile soils. It is not sensitive to acidity, and it almost equals barley in tolerance of alkali. Most rye is sown in the fall. It may be fertilized in a manner similar to that for fertilizing wheat.

Wheat (*Triticum*). Wheat is the common bread cereal of regions that have dry temperate climates, at least 90-day growing

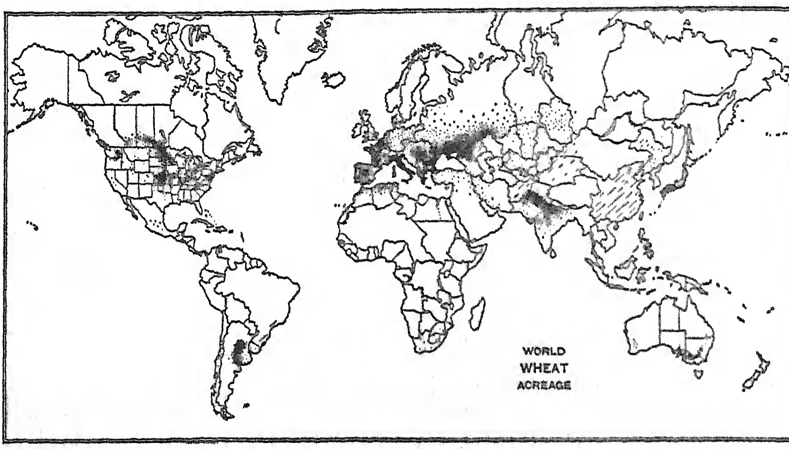

Fig. 104. World acreage of wheat (*Triticum*). In production, Russia ranks first; the United States, second; Canada, third; India, fourth; France, fifth; Argentina, sixth; and Australia, seventh.

seasons, and not less than 9 inches of rainfall, except where irrigation is practiced (Fig. 104).

Although wheat may be grown successfully on widely different soils, it should not be grown for milling purposes on weak, "white-alkali" lands. Among the most famous wheat soils are silt loams and clay loams that are rich in organic matter, such as the prairie soils and the black-earth soils (Chernozem) of steppes and short-grass plains.

From his study of the chemical composition of wheat plants (grown under field conditions), Pierre (Fr., 1862-1864) concluded that these plants take up most of their nutrient elements during the earlier stages of growth. Gericke (1925) has obtained similar results regarding phosphorus. Wilfarth and co-workers (Ger.,

1905) found that the total weight of mineral elements markedly decreased during maturity. Davidson and LeClerc (1917) and others have found that wheat plants may absorb nitrate nitrogen during heading stage, with considerable increase in protein content of the kernels (Ch. 22).

Results of laboratory studies agree rather closely with field results regarding the requirement of wheat for nitrate nitrogen. Hutchinson and Miller (Eng., 1908) have obtained results showing that, although wheat plants could utilize ammonic nitrogen directly, they grew best with the nitric form. Under a wide range of soil and climatic conditions, comparable results of fertilizer tests with wheat indicate that, on acid soils, nitrates are somewhat superior to ammonium compounds and ammonia-forming salts. Pirschle (Ger., 1931), working with plants in continuously renewed cultures, found that wheat plants responded better to nitrate than to ammonium nitrogen in alkaline and strongly acid mediums, that the two forms of nitrogen were equally effective in slightly acid mediums, and that mixtures of both gave better results than either when used alone.

Wheat, like barley and oats, commonly follows fertilized crops in rotation systems.

When called for, phosphate and potash (with some nitrogen) should be applied to winter wheat in the fall at rates of from 400 to 500 pounds of superphosphate per acre; and when necessary, from 50 to 75 pounds of muriate of potash. A mixture analyzing about 2 percent N, 12 or 16 percent P_2O_5, and 4 percent K_2O may be used at the rate of about 400 pounds an acre.

Fall applications of nitrogen salts, particularly of nitrate of soda, to winter wheat on the more permeable soils are not advisable, for the reason that heavy losses of nitrogen may occur during winter and early spring. Application of most of the nitrogen fertilizer in the spring before or about the time growth starts is generally regarded as the best practice—at rates of from 100 to 150 pounds an acre as top-dressing or by means of a grain drill (with fertilizer attachment) drawn preferably at right angles to the wheat drillrows. On deep heavy soils, ammonium salts and "lime nitrogen" may be applied in the fall.

For spring wheat, 200 pounds per acre of superphosphate or a suitable complete fertilizer like a 4–12–4 mixture may be applied in the drillrow with the wheat. In a study of methods of applying

mixed fertilizers for wheat, Duley (1930) obtained decidedly best results from drillrow applications, as compared with broadcasting.

COTTON (*GOSSYPIUM*)

Although of tropical origin, cotton is now grown in many places between 40° N. and 30° S. latitudes, where the summer temperature is warm both day and night. This crop is grown on widely different soils, but black prairie soils like those of Texas and rich alluvial soils like those along the Mississippi and the Nile produce the highest yields. According to Shantz and Piemeisel (1927), the water requirement of cotton plants varies from 443 to 657 pounds. Cotton is known as an excellent alkali-resistant crop.

The principal product of cotton is lint, the chemical composition of which is carbon, hydrogen, and oxygen. Notwithstanding the fact that lint is made from carbon dioxide and water, cotton requires rather liberal supplies of nutrient elements. The period during which these nutrients are absorbed, rate of absorption, their distribution within the plants, preference of nitrogen, and soil reaction have an important bearing on rational fertilizer practices.

White (1914) made a study of the chemical composition of cotton plants (tops) grown under field conditions, and found that the plants absorbed two thirds of the nitrogen they required, three fourths of the phosphorus, and nearly two thirds of the potassium by the time the first blooms appeared. The nitrogen and phosphorus constituents increased materially after the appearance of the first open bolls. Similar results have been obtained by Kudrin (Russ., 1929). Results of these and other investigations indicate that cotton requires considerable nitrogen after boll formation sets in; and experiments have shown that the best time to apply additional nitrogen, when soils are unable to supply adequate quantities, is when "squaring" begins or about 20 days after "chopping," or thinning out of the crop.

Conflicting results regarding "preference" of cotton for ammonic (NH_4) or nitric (NO_3) nitrogen may be explained on the basis of the reaction of the mediums or the presence or absence of available calcium and magnesium. Pirschle (Ger., 1929) found that within a narrow range around pH 7, ammonic nitrogen gave as good growth as nitric nitrogen, and that between reactions of pH 5 and 7, nitric nitrogen gave far better growth.

According to Naftel (1931), in culture solutions that contain both ammonic and nitric forms of nitrogen, cotton plants may absorb more of the first form than the second during the first 3 or 5 weeks; after that more nitric nitrogen may be absorbed. This investigator found that absorption of ammoniacal nitrogen increased as the acidity of the mediums decreased; whereas the intake of nitrate nitrogen was only slightly affected by the reaction. The greatest quantity of nitrogen was usually absorbed when the reactions of the mediums were pH 6. Absorption of nitrogen was greatest when both forms were present. Results obtained on field plots agreed well with those obtained in the laboratory. Tiedjens and Robbins (1931) have observed that cotton plants could assimilate ammonic nitrogen from culture solutions only when the reaction of the solutions was above pH 6.

Laboratory and field results indicate that basic nitrogen fertilizers are superior sources of nitrogen for cotton on medium-acid and strongly acid soils; and that under favorable conditions in regard to soil reaction or available calcium and magnesium, best results may be obtained when ammonium salts are included in fertilizers that are applied at planting time.

Fertilizing cotton. On alluvial soils like those of the Mississippi Delta, nitrogen is commonly the only element required. This need may be supplied by from 150 to 200 pounds of nitrogen fertilizer per acre. On black prairie soils, some superphosphate (150 to 200 lb.) is commonly required in addition to nitrogen. On uplands and soils of the Atlantic Coastal Plain, nitrogen, phosphorus, and potassium are generally needed. From 75 to 80 or more percent of the nitrogen may be applied in the form of water-soluble materials.

On the heavier-textured soils, the fertilizer materials may all be applied as a complete mixture at planting time; whereas on soils that contain much sand, it is desirable to apply from one half to three fourths of the total nitrogen as side-dressing at about chopping time or when squaring begins (35 or 40 days after planting). Rogers (1932) has reported highest average yields in South Carolina from side-dressing with half the nitrogen (nitrate) 3 weeks after chopping.

Complete fertilizers for cotton are commonly used at rates of from 400 to 600 pounds to the acre, such as 6(N)–6–3, 4–10–4, and 6–10–4 on sandy soils of the Coastal Plain, 5–10–3 and 5–10–4 on

the Piedmont Plateau, 8–8–8 on brown upland soils (loess), and 8–8–4 on red prairie soils.

Side-dressing cotton with easily soluble fertilizers like nitrates and ammonium salts at rates varying from 100 to 150 or more pounds to the acre is advisable on sandy and poor upland soils, to supplement the fertilizer applied at planting time. For best results generally, the side-dressing fertilizer should be lightly covered or mixed into the topsoil material.

Much depends on proper application of fertilizers. Precaution should be taken to avoid injury to the seed and seedlings, yet at the same time the fertilizer should be placed near enough to the seed to be immediately available to the young plants, to favor growth, early blooming, fruiting, and maturing. When all conditions are considered, best results may be obtained when the fertilizer is placed in bands on both sides of the seeds, about 1½ or 2 inches from them, and from 1 to 2 inches below the level of the seeds.

FRUIT TREES

Apples (*Malus* spp.). Among the many tree fruits, apples are most widely distributed. With the exception of certain varieties, this fruit is less restricted on account of soils than many of the staple crops. Apple trees require an adequate supply of water both summer and winter; hence the importance of favorable subsoils. Production of apples in the United States in commercial quantities does not extend very far below the line of 79° F. average summer temperature for June, July, and August. Northern limits are determined by dry winter winds.

Under orchard conditions, apple trees seem to obtain adequate supplies of phosphorus and potassium from the soil reserves. After a thorough study of experimental data, Potter (1929) has concluded that direct benefit from complete fertilizers over nitrogen alone is open to question, particularly during the first 100 years. Probably on very poor soils some benefit might accrue. Phosphates and mixed fertilizers are commonly used in orchards to benefit cover crops that are grown to conserve soil nitrogen and to provide sources of organic matter. Fertilizing apples consists primarily in supplying the trees with adequate nitrogen (Ch. 9).

There is no conclusive experimental evidence to show that, under normal orchard conditions, one source of nitrogen is superior to another, excepting conditions of very acid soils, when nitrates

may be best. The ability of apple trees to utilize ammonic nitrogen has been investigated by Tiedjens and Blake (1932) who have found that they (*Delicious*) can absorb and assimilate nitrogen directly from ammonium sulphate in slightly acid, neutral, and alkaline mediums, with greatest assimilation at pH 6.5. Varieties seem to respond differently.

Soil reaction may be an important factor in fruit production. Excessive acidity resulting from continual use of sulphur sprays and acid-forming chemical fertilizers may affect unfavorably not only nitrification, but also availability of the mineral nutrients. Excessive acidity calls for the use of agricultural lime. Supply of soil organic matter is another important factor (Ch. 18).

In their study of comparative effects of nitrogen fertilizers on bearing apple trees in poor vegetative condition, Schrader and Auchter (1925) have concluded that such trees will respond to both nitrate of soda and sulphate of ammonia, but that response the first season, at least, may be expected to be in favor of the nitrate.

Time of applying nitrogen is an important factor. Applications made in the spring about 4 or 6 weeks before blooming time generally produce more favorable effects on set of fruit, fruit, and growth than fall applications, particularly in initial applications. The nitrogen fertilizers are broadcast evenly around the tree under the outer branches.

Rate of application varies with culture methods and age of trees: In sod orchards, annual applications may range from ¼ pound for 1-year-old trees to 8 pounds for 30-year-old trees. In cultivated orchards, fertilizers are used to benefit the cover crops; but when additional nitrogen is required, about half the quantities may be used per tree as in sod orchards.

The value of nitrogen for apple trees was not established until during the early years of the present century, in experiments by Ballard in California and Oregon, by Ballou in Ohio, and by Stewart in Pennsylvania. Prior to that time it was thought that potassium was the element most needed by fruit trees, and probably phosphorus, and that nitrogen would prove to be antagonistic to fruit production.

Citrous fruits (*Citrus*). On the heavier-textured soils, as in California, oranges, grapefruit, lemons, and tangerines require nitrogen as do apples. The quantity of nitrogen (N) required

to the acre annually varies from about 200 to 350 pounds (about 2 to 5 lb. per tree), half of which should be applied in the form of barnyard manure or leguminous green manure. Nitrates and ammonium salts may be used to supplement the manures. Too high a degree of acidity or alkalinity may be harmful.

Manures may be applied during late summer or fall, and incorporated into the soils. The nitrogen salts are usually applied at different times—the first and heaviest application, before the trees come into full bloom; and subsequent applications, at diminishing rates at intervals of 4 or 6 weeks.

Under Florida conditions of sandy soils with low nutrient content, citrous trees require nitrogen, phosphorus, and potassium. As with apples, no carrier of nitrogen or of potassium has been found superior to any other, although nitrate of soda and sulphate of ammonia have been commonly used. Superphosphate (16-percent) is the common source of phosphorus. Successful systems of grove management call for the use of organic matter either as barnyard manure or as green manure, applications varying according to sand content of the soils.

Fertilizers should be broadcast evenly around the trees as far as the roots extend, and rate of application may vary according to tree spread or diameter of the tops. The need for the three elements—nitrogen, phosphorus, and potassium—does not necessarily call for the use of complete mixtures. The official fertilizer programs [2] call for the application of nitrogen three times a year (spring, summer, and fall). About ¼ pound of nitrate of soda or ⅕ pound of sulphate of ammonia, or equivalent in other materials, should be applied for each foot of tree spread. Phosphorus should be applied once a year (summer, April-June)—one pound of superphosphate, or equivalent in other materials, for each foot of spread. For trees over 20 years old, half this quantity should be applied. Potassium may be applied twice a year (summer and fall), at the rates of ⅙ pound of sulphate or muriate of potash for trees under 10 years of age, and ⅕ pound for older trees or those that appear to need more potassium.

Owing to rather large accumulations of available phosphorus and potassium in the soils of old groves, some growers eliminate applications of phosphate and potash entirely for 2, 3, and 4 years without affecting the yields.

2 CITRUS FERTILIZER PROGRAMS FOR FLORIDA. Series C, Florida Agr. Ext. Service. April, 1932.

Peaches (*Amygdalus persica*). Peaches require a climate free from severe winter temperatures and injurious spring frosts. Best soils are sandy loams free from alkali.

In studying the nutrition of young trees in culture solutions, Davidson and Shive (1934) found that peach trees in mediums that have pH values of about 6 can utilize ammonic nitrogen; and at pH 4, best growth was made with nitrate nitrogen. From 10-year experiments under Georgia conditions, McKay (1930) reported results showing that peach trees responded best to nitrogen-potassium treatment; and that maturity was hastened by phosphate fertilizers. Nitrogen retarded maturity to a marked degree. In other places phosphorus and potassium have produced no appreciable results.

Nitrogen fertilizers may be applied in the same manner as for apples, about blossoming time, at rates ranging from ½ pound for 2-year-old trees to 5 or 6 pounds for trees 8 years old and older. On sandy lands and poor soils, potassium and some phosphorus may be required as well as nitrogen.

Successful orchard management calls for the use of cover crops.

Small fruits. Inasmuch as grapes (*Vitis*) have been grown throughout historic times, their culture is well known. They can grow on rather strongly alkali and acid soils, and they respond to nitrogen fertilizers, principally. Nitrates or ammonium salts may be applied preferably in the spring just before plowing time, at the rate of 250 or 300 pounds to the acre. Two or three hundred pounds of superphosphate may be used per acre to benefit the cover or green-manure crops which are commonly grown in vineyards.

Strawberries (*Fragaria*) have been found to grow and fruit better in soil mediums of acid than in those of alkaline reactions. Waltman (1931) has reported results from which one may conclude that strawberries require comparatively large quantities of phosphorus. It would seem that an acid medium favors utilization of phosphorus by these plants. This crop usually requires a light application of easily soluble nitrogen fertilizer early in the spring of the first year after planting, applied at the rate of about 100 or 150 pounds to the acre when growth starts. An early fall application of complete fertilizer is important for the setting of fruit buds for the crop the following year. Davis and Hill (Can.,

1928) have found phosphorus fully as important as, if not more than, nitrogen in influencing the set of fruit.

Blackberries (*Rubus*) grow best on deep, moist, slightly acid fine sandy loams that contain considerable organic matter. Rational use of manure and of complete fertilizers, such as 4–8–4 and 4–8–6, are desirable for this crop when conditions indicate the need for fertilizers.

Red raspberries (*Rubus*) grow best on moist, fertile loams that are somewhat acid. Best results may be obtained when this crop is fertilized with manure or complete fertilizers.

GRASSES

Permanent pastures. Continual grazing of permanent grasslands, together with selling off of milk, beef, mutton, and wool, reduces soil productivity, which necessitates returning to such lands supplies of the nutrient elements. In humid regions bunching of grasses commonly indicates a lack of vigor which may result from unfavorable soil conditions, such as acidity.

The standard fertilizer long used for improving the better grazing lands in England has been basic slag, applied at rates ranging from 400 to 1,000 pounds to the acre at intervals of 4 or 5 years. This fertilizer has proved to be beneficial in other European countries and elsewhere, particularly on acid soils. On light and poorer soils, potash in addition to phosphate may be helpful.

At Rothamsted, England, continual use of nitrogen, together with "minerals," has increased the grasses in the pasturage to 94 percent and decreased the legumes to less than 1 percent. Generally, on lands that have been exhaustively grazed, addition of mineral elements and nitrogen is desirable to increase the yield and quality of the pasturage. Many strongly acid soils call for initial applications of agricultural lime to favor the growth of the better grasses and to create better chemical conditions in the soils. On acid soils that are well supplied with organic matter, improvement may be effected most economically through the use of lime and superphosphate or basic slag.

Certain types of rotational grazing allow for intensive use of fertilizers on pastures, particularly of nitrogen.

Rotational grazing consists in moving livestock from field to field or from paddock to paddock so as to allow each field to be grazed in turn and then shut up to allow fresh growth of the

grasses. Tethering, a simple but intensive form of such grazing, has long been practiced in some of the European countries.

A close-grazing rotational system of pasture management, which originated at Hohenheim, Germany, in 1917, is based on two procedures: (1) pasturing while the grasses are young and rich in protein; and (2) top-dressing liberally with complete fertilizers, plus subsequent top-dressings with about 100 pounds of nitrogen fertilizer to the acre, usually when each paddock is released for its 2- or 3-week rest. The purposes of the nitrogen top-dressings are to assist in rapid recovery of the grasses and to increase the protein content of the herbage. This intensive system calls for liberal supplies of the mineral elements, fencing of the grazing area into from 4 to 8 subdivisions for separate grazing, and provision of water for the livestock. High-producing milk cows are usually turned in first, and these are followed by "low-producers" and young animals, so as to effect greater returns and close and uniform grazing.

The use of adequate fertilizer on pastures may increase carrying capacity, materially lengthen the grazing season, thicken and improve the turf, reduce weeds, and eliminate injury from white grubs.

Ordinary permanent pastures are commonly grazed rotationally, and, if soils are acid, they may be improved by applying lime. Additional improvement may be effected by top-dressing such pastures early each spring with 150 or 200 pounds an acre of easily soluble nitrogen fertilizer, with 300 or 500 pounds of superphosphate once in 4 or 5 years, and if required, with 100 or 200 pounds of potash fertilizer now and then. Initial fertilizer treatment may consist in applying an equivalent quantity of complete mixture. A second application of nitrogen fertilizer may be made later in the season each year, at rates varying from 150 to 200 pounds an acre.

Soil reaction or available calcium and magnesium is an important factor in determining the species of grasses and other plants in permanent or natural pastures (Ch. 15) and in affecting the quality of the pasturage. Atkins and Fenton (Scot., 1930) found that when cows and sheep were allowed to roam freely, they grazed closely on herbage growing on soils having pH values of 6.5; they grazed on most sites where pH values were above 5; but where soil acidity was greater than pH 5, there was practi-

cally no grazing. Several investigators have observed preference by livestock for fertilized pasturage.

Lawns. Lawn grasses grow best on loams and silt loams that are well supplied with mineral nutrients and organic matter, notwithstanding the fact that some grasses can tolerate high degrees of acidity that are thought to be unfavorable for certain weeds like dandelions and plantains. It is generally conceded that the most effective factor in weed control on lawns is grass that is kept thick and vigorous by adequate supplies of water and nutrients.

In the preparation of a seed bed for grass, it is desirable to adjust the soil reaction to about pH 6.2 or 6.5, and to provide adequate soil reserves of organic matter, phosphorus, and potassium. Subsequent fertilizer treatment may then consist in top-dressing with manure in the fall or with nitrogen early in the spring, with applications of superphosphate and muriate of potash once in 4 or 5 years. From 1 to 3 subsequent applications of nitrogen fertilizer may be made at the rate of about 100 pounds an acre or about 1 pound to 400 square feet. Lawns should be thoroughly watered after each application of fertilizer salts, particularly nitrogen. When a lawn reaches a high state of improvement, it is not necessary to fertilize it frequently nor every year, unless the soil is very poor.

Poor lawns on acid soils can be greatly improved by top-dressing them annually for a few years with agricultural lime, and by adding manure, organic fertilizers, or complete fertilizers like a 6(N)–8–4 plus 2 or 3 subsequent top-dressings with nitrogen fertilizer. Of the nitrogen fertilizers, the basic ones are desirable. Neutral fertilizer mixtures that carry both nitrate and ammonium forms of nitrogen offer distinct advantages (Ch. 22).

Nitrate fertilizers are especially beneficial for lawn grasses if they are applied early in the spring when the soil is cold and wet. Beaumont and Rohde (1930-1932) observed that bluegress, timothy, English ryegrass, redtop, red clover, and alsike clover, grown in culture solutions, seemed to assimilate nitrate nitrogen better than nitrogen from ammonium sulphate and urea, as indicated by growth, particularly during later stages. The clovers showed much better growth with nitrate nitrogen during early stages. Similar results with creeping bentgrass under field conditions have been reported by Sprague (1930-1934). In cultures, varying in pH

from 4.8 to 5.1, Colonial bentgrass used NH_4 nitrogen better than Kentucky bluegrass.

According to Cooper and Wilson (1930), grasses like Kentucky bluegrass, which require fertile soils and much radiant energy for optimum growth, are usually not very tolerant of shade (see Index).

Lawn grasses on soils adequately supplied with calcium and magnesium can withstand dry conditions better than the same grasses on acid soils. The same may be said of grasses that are well supplied with potassium, as compared with plants that lack this element; but grasses on slightly acid soils and grasses which are adequately supplied with nutrients may be most vigorous of all.

Moss on lawns may be killed, and the grass made to grow in its place by top-dressing such areas, particularly if soils are acid, with hydrated lime and nitrate of soda at rates of 1 pound of the lime and ⅓ pound of the nitrate to 100 square feet. This treatment calls for a thorough sprinkling with water after the materials are applied. On old upland permanent pastures infested with haircap moss (*Polytrichum commune*), Beaumont (1932) has observed that nitrate of soda and nitrate of potash have direct killing effects on the moss, but not on the grass, when applied at the rate of 60 pounds of nitrogen (N) to the acre, owing to the toxic action of the sodium and potassium cations in association with the NO_3^- ions. As the toxic action is cumulative, several lighter applications will effect killing.

The manner of cutting grasses is a very important factor in lawn management, and special attention should be given to the height and frequency of cutting.

Adaptation of lawn grasses. Adaptation of lawn grasses in the United States, as indicated by Westover and Enlow (1931), is shown in Figure 105. The bentgrasses (*Agrostis*) are most likely to succeed in the northeastern States and in the northwestern part of the Pacific States. These include the following kinds:

Colonial bentgrass (*A. tenuis*). Grows best on the heavier-textured and moderately acid soils, can tolerate very strong acidity and medium alkalinity, and can withstand close cutting.

Redtop (*A. alba*). Tolerant of adverse soil conditions. No other grass will grow under so wide a range of conditions. Best wet-land grass, yet strongly drought resistant. Will grow on very poor and strongly acid soils. Not a good lawn grass to seed alone.

Seaside bentgrass (*A. maritima*). Grows best on somewhat acid, rather open soils. Can withstand frequent salt-water washings. Can be kept closely cut.

South German bentgrass, mixed (*Agrostis*). Grows best on moderately acid soils, and can tolerate strong acidity.

Creeping bentgrass (*A. stolonifera*). Grows best on heavier-textured and moderately acid soils. Can withstand very close mowing. Propagated from stolons.

Velvet bentgrass (*A. canina*). Requires moderately acid soils. Can tolerate strongly acid conditions, medium alkalinity, and close cutting. Propagated from stolons.

In region 1, the following grasses are adaptable:

Bluegrasses (*Poa*). Grow best on neutral and slightly acid soils.
- Kentucky bluegrass (*P. pratensis*). Superior for general use.
- Canada bluegrass (*P. compressa*). Can grow on poor clay soils.
- Rough bluegrass (*P. trivialis*). Best adapted to cool, moist soils, and thrives better than any other grass in the shade of buildings.
- Annual bluegrass (*P. annua*). Can tolerate rather acid conditions if soils are well supplied with nutrients.

Fescues (*Festuca*) and other grasses.
- Red fescue (*F. rubra genuina*). Can tolerate strongly acid conditions, adapted to sandy soils, and does fairly well on poor soils. Suitable for areas that are shaded by trees.
- Chewings fescue (*F. rubra* var. *fallax*). Like red and sheep fescues, can tolerate unfavorable conditions. Suitable for places that are shaded by trees.
- Sheep fescue (*F. ovina*). Best suited for poor soils, especially those that are sandy.
- Fine-leaved fescue (*F. capillata*). Grows best in neutral and slightly alkaline sandy loams. Very desirable for shady golf tees.
- Meadow fescue (*F. pratensis*). Tolerant of shade and strong soil acidity.
- Bentgrasses (*Agrostis*). Suited to acid-soil conditions.
- Perennial ryegrass (*Lolium perenne*). A short-lived perennial.
- Italian ryegrass (*L. multiflorus; L. italicum*). Short-lived perennial. Usually succumbs to hot, dry weather.

In region 2, the grasses that are generally best suited include the following:

Bermuda grass (*Cynodon dactylon*). Best suited for lawns generally. Makes best growth on slightly acid clayey and silt-loam soils.

Italian or Australian ryegrass. May be sown on Bermuda-grass lawns in the fall; and when the ryegrass dies out the following spring, the Bermuda grass comes back, especially if the lawn is fertilized.

St. Augustine grass (*Stenotaphrum secundatum*). One of the best to

tolerate shade when sufficient moisture and nutrients are available. Valuable as a sand binder. Propagated by stolons.

Texas bluegrass (*Poa arachnifera*). Makes best growth during winter months.

At higher altitudes, Kentucky bluegrass and redtop may be used; and for low well-drained areas, crested dogtail (*Cynorurus*

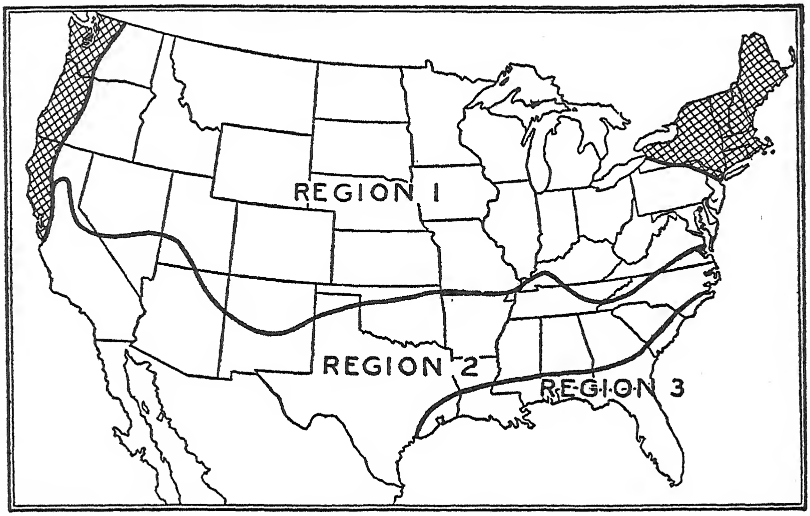

Fig. 105. Adaptation of grasses in the United States.

cristatus), creeping bentgrass, and rough bluegrass; and in suitable places, Colonial bentgrass.

In region 3, the following grasses are adaptable:

Carpet grass (*Axonopus compressus*). Especially desirable on moist soils.

Bermuda grass. Desirable for drier areas, especially on heavier-textured soils.

Centipede grass (*Eremochoa ophiuroides*). Most desirable where winters are mild. Will grow on any except poorly drained soils. Propagated by stolons.

St. Augustine grass. An excellent grass for shady places.

Golf courses. Bentgrasses (except redtop), red fescue, Chewings fescue, Bermuda grass, and carpet grass are commonly used on putting greens; Colonial bentgrass, creeping bentgrass, fine-leaved fescue, annual bluegrass, rough bluegrass; Bermuda grass,

and carpet grass, on tees; and bluegrasses, Colonial bentgrass, and Bermuda grass, on fairways.

Maintenance of good turf on putting greens usually requires intensive cultural methods, commonly involving the use of fertilizers, fungicides, and insecticides. Various methods of treatment and kinds of fertilizers are used. Greens are commonly fertilized liberally with complete and nitrogen fertilizers, applied as top-dressings in the dry state or in solution; and the fairways are commonly top-dressed with superphosphate and organic fertilizers.

From their investigations of the effects of pulverized limestone and oyster shells, hydrated lime, and fertilizers on turf grasses in New Jersey, Sprague and Evaul (1930) have obtained, among others, the following results:

1. Use of barnyard manure intensified the weed problem.
2. Weeds were reduced on plots that had been made strongly acid, but not more so than on plots that had been heavily limed and fertilized with nitrogen. (Control of weeds by making soils acid is regarded as unwise, owing to the fact that certain weeds can withstand strong acidity as can "acid-tolerant" grasses.)
3. Very strong acidity did not allow healthy grass growth throughout the season.
4. White clover (Dutch, *Trifolium repens*) was held in check by close cutting, combined with use of nitrogen fertilizers. Under these conditions, lime did not increase clover.
5. Strongly acid soils were less able to maintain vigorous growth of bentgrasses than soils that were slightly acid or neutral in reaction.

White and co-workers (1930) have found that mercury compounds applied on greens reduced the beneficial activity of nitrifying organisms, particularly under strongly acid conditions; whereas on limed greens, mercury compounds produced no significant harmful effects.

ROOT CROPS

Potatoes (*Solanum tuberosum*). Potatoes (Irish) show a preference for regions of comparatively cool and uniform temperature and moderate rainfall. They grow best on well-drained loamy soils that contain considerable organic matter, and that have pH values ranging between 6.0 and 6.3. They can be grown on weak white-alkali soils.

Of the nitrogen fertilizers, sulphate of ammonia has given best results in many places, as compared with nitrate of soda; but in

other places the nitrate has proved to be superior. Under strongly acid conditions, basic fertilizers may prove to be desirable. On soils susceptible to scab disease but with reactions adjusted for scab control, neutral fertilizers may be used to maintain proper soil reaction (see Index). In some places where soils are free from scab, mixtures of sulphate of ammonia and nitrate of soda have given better results than either of the two materials when used alone in equivalent quantities. Liming scab-free acid soils may be indirectly beneficial for potatoes, in favoring the growth of legumes.

Proper balance between nitrogen and potassium seems important in the nutrition of potatoes. Potato plants absorb nitrogen and phosphorus freely during the earlier stages of growth, which probably explains why early application of fertilizers usually gives best results.

Potatoes remove from soils comparatively small quantities of phosphorus, yet they require an abundance of this element for satisfactory growth and yields. This, therefore, is one of the crops most sensitive to deficiency of available phosphorus. The fact that large quantities of phosphorus are added to New Jersey potato soils, and that this element has been found by Blair and Prince (1928) to accumulate in such soils, leads one to doubt the necessity of applying it every year.

Although sulphate of potash is regarded as superior to muriate of potash for potatoes in some European countries in affecting yield and quality, under conditions and practices in the United States, muriate seems to give as good results as the sulphate. Russell (Eng., 1931) has given results of quality tests indicating that kainite has given the poorest cooking quality, probably because of excess chlorine.

In general farming, potatoes are commonly grown on sod lands, particularly clover lands, and are fertilized with manure at rates of 10, 12, and more tons to the acre. On many soils it is desirable to supplement the manure with phosphate.

In potato-growing districts, the use of complete fertilizers with satisfactory ratios of nitrogen, "phosphoric acid," and "potash" is advisable if applied at planting time. The nitrogen may be derived from water-soluble sources and organic materials. Analyses vary widely. Among those commonly used may be listed 3(N)–12–12, 4–8–4, 4–10–6, 5–8–5, 5–8–7, and 7(N)–6–5. Rates

of application range from 500 to 3,000 pounds to the acre. A common practice is drillrow application, in which the fertilizer is dropped in a wide band with the seed at planting time, mixed with soil material in the drillrow before planting, or placed on both sides of the seed pieces (Fig. 103).

Inasmuch as this crop is planted in rows, it may be side-dressed with potash and soluble nitrogen fertilizers. When conditions indicate, such applications should be made not later than 4 weeks after planting.

When, in humid regions, liberal quantities of complete fertilizers are used on light sandy soils, it may be advisable, to lessen loss by leaching, to apply half the quantity of fertilizer before or at planting time and the other half when the ridges are leveled, just before the sprouts appear above ground.

Sugar beets (developed from *Beta vulgarus*). Sugar beets give best returns on deep, fertile, loamy soils that are well drained and aërated. Storage of high percentages of sugar in the roots of sugar beets is favored by cool, fair weather. Soil reaction is an important factor. Best beet soils, generally, are neutral or slightly alkaline. Although sugar beets are most alkali-resistant, it has not been profitable to grow them on very strong alkali soils. Gorbing (Ger., 1930) found that when sugar beets were planted in pots filled with soil material of different degrees of acidity, the fine hairlike roots visibly deteriorated in the strongly acid layers, regardless of the depth at which those layers were placed. Newlands (Scot., 1928) observed that when soil acidity was below pH 5.3, or when the readily extractable soil calcium fell below 0.12 percent, growth was poor or failed.

Under general field conditions nitrate of soda has universally proved to be the best nitrogen fertilizer for sugar beets. Nitrogen applied in large quantities late in the season retards maturity, lowers quality, and reduces the sugar content; whereas on soils that are poor in nitrogen, according to Herke (Ger., 1911), nitrate of soda with phosphate and potash increases sugar content without injury to quality.

Potash fertilizers on potassium-deficient soils increase quality, sugar content in the beets, and resistance to certain diseases.

Soils on which sugar beets are grown in the United States commonly show a marked deficiency of available phosphorus (Fig.

106); whereas in Germany the principal deficiency in such soils is nitrogen.

Barnyard manure is commonly used for this crop. Where it is not available, commercial fertilizers are used. On phosphorus-deficient soils, applications of 500 pounds of 16-percent superphosphate to the acre, or its equivalent in more concentrated forms,

Fig. 106. Sugar beets. Left (8 rows)—Plants that had received no phosphate. Right—Earlier growth of plants resulting from the use of phosphate. (U. S. Dept. Agr.)

usually meet requirements. Elsewhere, on mineral soils, complete mixtures, such as 2–10–8, 4–10–8, 3–12–12, and 3–12–20, may be used; and on peat and muck soils, mixtures, such as 0–8–24, 0–8–32, 0–20–20, and 0–15–30, are preferable. Application of fertilizers before planting usually gives best results, although drillrow application at planting time may give excellent returns, particularly during dry seasons. The lower-analysis mixtures may be used on unmanured soils at the rate of about 500 or 600 pounds to the acre. Here excellent results may be obtained by plowing under 300 or 400 pounds and applying from 150 to 200 pounds in the drillrow.

Under ordinary conditions, side-dressing or top-dressing with nitrate is unnecessary; but in districts of heavy rainfall and well-

drained, light loamy soils, reserving a part of the nitrate applied as side-dressing after blocking and thinning may be done with profit.

VEGETABLES

Vegetables require liberal quantities of nitrogen throughout the growing season, particularly the leafy ones like cabbages, cauliflower, spinach, Swiss chard, lettuce, and celery. Heavy applications of manure or complete fertilizers, or both, are usually made, and likewise provision for watering (Fig. 12). It is desirable to provide and maintain adequate supplies of soil organic matter.

Vegetables are particularly responsive to nitrate fertilizers, and top-dressings and side-dressings with nitrates are commonly applied. On fine loamy white sand, under Florida conditions, Skinner and Ruprecht (1930) have obtained better results with celery and lettuce with a mixture of nitrate of soda and organic materials, such as cottonseed meal and tankage, as sources of nitrogen (with phosphate and potash) than with nitrate as a single source of nitrogen.

Experimental evidence shows that when nitrogen, phosphorus, and potassium are needed, the mineral elements, together with some nitrogen, should be applied prior to or at planting or transplanting time, and that additional nitrogen should be applied as side-dressing. Leafy vegetables may be greatly benefited by side-dressings. The best time for making after-planting applications of nitrogen fertilizer for fruit vegetables like cucumbers and melons is when the first clusters of blossoms are opening. Applications may range from 150 to 300 pounds to the acre. On alkaline soils, reaction should be kept below pH of about 7.5; and on acid soils, above about pH 6 (pp. 286-290, Fig. 74).

Tomatoes (*Lycopersicon esculentum*). Tomatoes, which are a warm-season crop, may be grown under a wide range of soil conditions. Adequate supplies of soil calcium and magnesium are desirable. Clark and Shive (1934) have demonstrated that younger tomato plants growing in continuously renewed culture solutions can absorb and assimilate ammonium nitrogen more readily at pH 7 than at pH 4. Nitrate nitrogen can be most efficiently assimilated by plants in solutions having pH values of 4 and 5. Older plants are not affected by reaction as are younger plants.

In his studies of the nutrition of tomato plants, Heydemann (Ger., 1928) found that assimilation of nitrogen, calcium, potas-

sium, and phosphorus proceeded at an equal rate for a time, after which potassium and nitrogen were used more rapidly. He has suggested that fertilizer be applied before or at planting time, because all nutrients are required from the start. An adequate moisture supply is particularly required during the period from fruit-set to maturity.

Meyer (Ger., 1929) has shown that tomato plants are very sensitive to phosphorus deficiency in soils. Under phosphorus-deficient conditions, they will show typical malnutrition symptoms within 8 or 10 days after germination.

Fruitfulness in tomato plants is determined by a proper balance in the plants between carbohydrates and nitrogen (Ch. 20). So long as the plants can accumulate carbohydrates and at the same time can obtain adequate nitrogen and minerals, they are both vegetative and fruitful, even though heavy applications of nitrate may be made.[3]

Manure is an excellent fertilizer for tomatoes. Soil conditions may call for a supplementary use of superphosphate at the rate of 40 or 50 pounds to 1 ton of manure. On unmanured land, complete fertilizers are used at rates ranging from 600 to 1,000 pounds to the acre, including such analyses as 4(N)–12–4, 4–16–4, and 4–10–8.

Tomato growers aim to supply the plants with small quantities of readily available nitrogen for early growth, with slowly available nitrogen until the blooming period, and with more readily available nitrogen after the fruit is set. (This seems to be in accord with the findings of Heydemann.) About two thirds of the fertilizer may be applied broadcast and worked into the seed bed before planting, and one-third (especially phosphate) applied in the drillrow at planting time. After the vines set a heavy crop, from 150 to 200 pounds an acre of soluble fertilizer may be applied between the rows (mainly nitrogen and potassium).

OTHER CROPS

Tobacco. For tobacco both soils and latitude vary widely. Value of the leaf is affected materially by soil and climate. To illustrate: Northern, shade, cigar-binder, and cigar-wrapper tobaccos are grown on fertile soils in Connecticut Valley; cigar-binder leaf, on heavily manured and fertile soils of Wisconsin; air-cured

3 WORK, PAUL. NITRATE OF SODA IN THE NUTRITION OF THE TOMATO. Cornell Univ. Agr. Expt. Sta. Memoir 75. 1924.

burley, on the fertile soils of the bluegrass region of Kentucky and in adjoining districts; and bright flue-cured tobacco, on light-colored sandy loams of Virginia, North Carolina, Georgia, and Florida.

Owing to their limited and shallow root systems and to their being leaf-producing crops, tobaccos require liberal quantities of nutrients. With bright flue-cured tobacco, it is important that the nitrogen supply be exhausted at the time of maturity to allow proper development of leaf of low-nitrogen content.

Results of field experiments show that agricultural lime has rarely produced any material increase in yields of tobaccos. However, on very strongly acid soils (pH below 4.8), the value of lime is generally recognized, inasmuch as such soils lack available calcium, and they may contain toxic manganese or aluminum, or both. In Connecticut, Morgan and co-workers (1929) found that soils that had pH values ranging from 4.8 to 5.6 produced the highest percentage of satisfactory crops; and that on soils with pH values above 5.6, crop injury from black root rot was prevalent. They warned against growing tobacco soils with pH values above 6 and below 4.8.

Experimental evidence, although somewhat conflicting, indicates that tobacco plants can assimilate nitric nitrogen (NO_3) better than ammonic nitrogen. Some results seem to indicate that at certain stages of growth the latter form is assimilated as well as or better than the former. Nitrate of soda is generally used in plant beds. Under field conditions, Hutcheson and Copley (1929) obtained highest increases in yields of bright tobacco in 7-year tests from nitrate of soda, but more satisfactory results when sulphate of ammonia and nitrate of soda were combined.

Working with cigar tobaccos, Anderson and co-workers (1932) have found but little difference in the effectiveness of six potash fertilizers. McMurtrey and co-workers, in Maryland, found muriate of potash harmful to fire-holding and other qualities.

Garner and McMurtrey (1930) have pointed out that in many tobacco soils the supplies of magnesium may not be sufficient to meet the needs of growing crops, and that in other soils there may not be adequate calcium to allow normal growth. Calcium deficiency inevitably induces magnesium toxicity in the plants. When both elements are deficient, plant growth is greatly reduced. Sulphur added in fertilizers may favor early growth.

Owing to the fact that chlorine is absorbed by tobacco plants with great ease, excessive quantities of this element may disturb carbohydrate metabolism, retard growth, and adversely affect the quality of the cured leaf. Accordingly, a satisfactory fertilizer for tobacco on many soils should contain, in addition to the major nutrient elements, from 20 to 60 pounds of magnesium to the acre, 50 or more pounds of calcium, about 25 or 30 pounds of sulphur, and from 20 to 30 pounds of chlorine. Too much available calcium may cause black root rot.

Cigar tobaccos are commonly fertilized with from 10 to 20 tons of barnyard manure to the acre. Manure may be supplemented with 600 or 1,000 pounds of complete fertilizer, such as 2–12–6 or 3–8–3, applied in the drillrows and thoroughly mixed with soil material within 10 days prior to transplanting. When no manure is used, fertilizer should be used to supply the equivalent of from 1 to 2 tons of 5–4–5 mixture per acre.

Johnson and Ogden (1930), Thomas (1930), and other investigators have found that some quickly available nitrogen like nitrate applied in the drillrows proves to be helpful in overcoming "brown root rot," or the effects of nitrate depression that may result when tobacco follows such crops as timothy, rye, and maize, or is planted on soils that contain much cellulosic material (Ch. 18). After-planting applications of fertilizer may not be advisable.

Bright flue-cured tobaccos are usually grown on soils that are naturally infertile. Materials equivalent to 800 or 1,200 pounds an acre of a 3(N)–8–6 mixture are recommended for the Piedmont Plateau, and of a 4(N)–8–5 mixture for the Atlantic Coastal Plain region. Two percent chlorine in a fertilizer is the maximum, and at least 2 percent magnesia (MgO). Magnesium may be supplied by dolomitic limestone, magnesium sulphate, or sulphate of potash-magnesia (Ch. 21). When heavy applications of fertilizers are made, it may be desirable to apply some of the quickly soluble nitrogen fertilizer as side-dressing.

Sugarcane (*Saccharum officinarum*). The growing of sugarcane is confined to tropical and semitropical regions. Deep, well-drained, fertile, and slightly acid to nearly alkaline soils are best. This is a two-season crop; ordinarily, it grows from 14 to 25 months before it is cut. In its culture, uniformly high temperature, strong sunlight, and adequate water are required.

In some places, soil conditions call for the use of phosphate and liberal use of potash fertilizers; but the most important requirement, generally, is nitrogen, which may be applied in different forms. In Hawaii, phosphates are commonly applied with the seed in the furrow at planting time; and on ratoon crops, with the subsoiler. A second application of phosphate (soluble) is made 2 or 3 months later. Potash fertilizers (200 to 600 or more pounds per acre) are usually applied during the first 5 months of growth, in one or two applications, at the base of the plants. Nitrogen fertilizers, at rates varying from 2½ to 3 pounds of nitrogen per ton of cane expected, are applied in from 3 to 5 applications at intervals of from 6 to 8 weeks. The last application is usually made at least several months before harvest. No broadcasting of fertilizers is practiced, although in big cane the only practical method of application is with irrigation water.

In Louisiana, best results may be obtained by using from 200 to 300 pounds of nitrogen fertilizer and 200 pounds of superphosphate to the acre, applied early in the "off-bar" furrow. Potash is also used, when called for.

It is important that the plants use up the nitrogen applied quickly, so as to allow proper maturing after full growth is attained.

Pineapples (*Ananas sativus*). Sideris and Krauss (1930) have reported results which seem to show that pineapple plants in cultures grow best with the nitric form of nitrogen, provided they are well supplied with iron; and that when ammonic nitrogen is used, much less iron is required. However, results of other experiments seem to indicate that the plants are able to assimilate all their nitrogen in the ammonic form. Under field conditions, it is believed that they grow best in acid soils; hence the common or preferred use of sulphate of ammonia.

An excess of basic elements is not advisable for pineapples. The Puerto Rico Agricultural Experiment Station has reported results showing that carbonate of lime injuriously affected the mineral nutrition of both rice and pineapples, causing chlorosis of the latter (see Index).

This crop grows 2 years before it yields its first fruit; thereafter it yields a crop annually, commonly for 2 years. According to Horner (T. H., 1930), a 33-ton crop of pineapples removes from the soil at the time of its maximum draft (at 19 months) about

490 pounds of nitrogen, 48 pounds of phosphorus, and about 1,200 pounds of potassium. In fertilizer practice, however, from 150 to 400 pounds of nitrogen, from 33 to 80 pounds of phosphorus, and from 80 to 160 pounds of potassium are applied per acre. Iron is also required (Ch. 20). The nitrogen fertilizer is supplied in from two to four applications per year, applied in the basal leaves. Complete fertilizers are commonly used, with supplementary applications of sulphate of ammonia.

Mushrooms (*Agaricus campestris*). Cultivated mushrooms are quite different economic plants, particularly as regards nutrition. They do not manufacture carbohydrates and proteins as do green plants. On the contrary, they, in a true sense, require food substances that have been synthesized by other organisms. Like all other fungi, mushroom plants are nonchlorophyllous and heterotrophic organisms, and they obtain all their nourishment from organic matter of the mediums on which they grow. Well-decomposed horse manure is commonly used as the source of their food requirements. Artificial manures may also be used with good success (see Index).

The composting of manures for mushrooms accomplishes four principal ends: (1) It removes soluble organic matter that is injurious to the growth of mushrooms; (2) it eliminates competitive organisms; (3) it removes easily decomposable substances that would otherwise favor development of other organisms; and (4) it makes the manure a more suitable medium for the mushrooms.[4]

In their study of the nutrition of mushrooms growing on composted manure, Waksman and Nissen (1932) have found that these plants feed largely upon lignins and proteins and to a lesser degree upon hemicelluloses, celluloses, and other complex organic compounds. These substances, as such, are not available for use by the fungi; they release certain enzymes which decompose and make the complex organic compounds soluble.

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REVIEW QUESTIONS

1. What is the role of soils in regard to the use of fertilizers? Explain.
2. Discuss the important factors that are involved in the proper use of fertilizers.
3. What conditions call for the different methods of applying fertilizers? Give examples.
4. What are some of the facts about barley on which to base proper fertilizer practice for this crop? About Indian corn?
5. Explain why nitrates are not commonly used for paddy rice, nor for pineapples.
6. Compare the use of fertilizers for wheat with that for oats.
7. Explain why side-dressing may prove to be most profitable for cotton. Why may it also prove to be beneficial for tobacco?
8. Point out the difference in fertilizing apple and citrous trees.
9. Explain and illustrate methods of rotational grazing of pastures.
10. Name the important points to be considered in making a lawn. Give examples.
11. Explain why top-dressing a Bermuda-grass lawn on a strongly alkaline soil with sulphate of ammonia or ammonium phosphate, as in southern Arizona, proves to be very beneficial.

12. What crop may be regarded as a nitrate crop?
13. What peculiar problems attend the fertilizing of sugarcane and bright flue-cured tobacco? How may these problems be met?
14. As regards fertilizer, how do mushrooms differ from other crops?
15. How do tilth, soil aëration, micro-organisms, organic matter, water supply, and soil reaction affect the efficiency of fertilizers?
16. When one considers the problem of citrous-tree decline on alkaline-calcareous soils (see p. 449, under "Indirect effects"), would sulphur be regarded as a fertilizer if its use under such conditions corrects the chlorotic condition of the trees?
17. If, as in warm regions, rapid nitrification takes place when nitrogenous fertilizing materials are applied (producing an excess of ammonia), how can economic use of fertilizer nitrogen be effected? Explain.
18. Gather facts relative to cultural practices for a world-wide crop like wheat or oats, and on the basis of these facts formulate a principle that may serve to guide one in fertilizing the crop.
19. Discuss the advantages in fertilizing a crop when one considers first the needs of the crop plants, growth habits, nutrient requirements, plant physiological factors, and soil reaction, and secondly, the soil, whether during the season it can meet all the requirements for optimum growth and maximum yield.
20. Discuss the idea of building up in a soil high "permanent" reserves of organic matter and plant nutrient elements with a view to producing maximum yields, regardless of kind of crop.

CHAPTER 24

CROP ROTATION AND SOIL FERTILITY

Crop rotation is orderly cropping which, on a given tract of land, calls for recurrent succession of different crops. For example, on a given field, we may grow Indian corn on clover sod the first year, wheat the second year, and clover the third; this would be a 3-year rotation. The fourth year corn is grown on clover sod again, and then wheat, followed by clover, and so on. Crop rotation implies recurrent planting of crops—not necessarily of all that may constitute a cropping system, but of the principal ones, at least—at intervals of 2, 3, 4, 5 or more years, depending on the cropping scheme.

To obtain annual yields of each crop grown in rotation, it is necessary to divide an area of land or a farm into subdivisions or fields and to alternate the crops on them according to the cropping plans.

The opposite of crop rotation is the one-crop system in which only one kind of crop is grown continually on the same land. Growing a crop in this manner is commonly called "continual cropping" and "continual culture."

Rotation a factor determining soil fertility. A study of long-continued field experiments in the United States and England has shown that rotation of crops is about 90 percent as effective as application of barnyard manure and complete chemical fertilizers in maintaining yields of wheat, maize, and oats.[1] Hence crop rotation must be considered as an important factor that affects soil productivity.

Evaluating crop rotation. The total benefits of crop rotation can best be compared with those of fertilizers, expressed in terms of crop yields. For such comparisons it is desirable to have results of long-continued field experiments. A series of comparable results with any crop should include yields obtained the same year under conditions of continual cropping, with and without ferti-

[1] WEIR, WILBERT W. A STUDY OF THE VALUE OF CROP ROTATION IN RELATION TO SOIL PRODUCTIVITY. U. S. Dept. Agr. Dept. Bull. No. 1377. 1926.

lizer, and under conditions of rotation, with and without like fertilizer.

Yields obtained from continual cropping without fertilizers may be regarded as being obtained from cultivation only. Thus in evaluating the benefits of crop rotation, three principal factors are

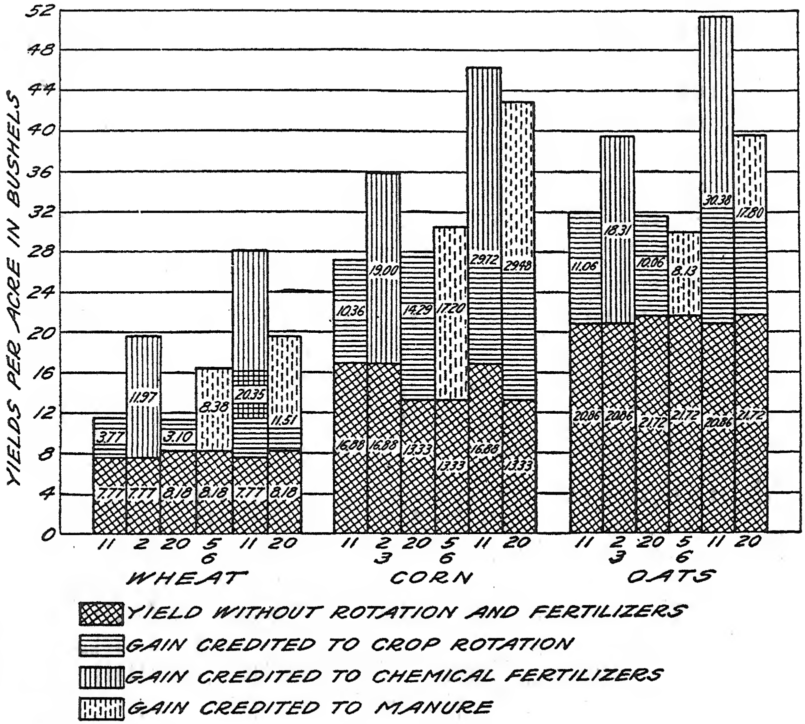

Fig. 107. Comparative effectiveness of crop rotation, complete chemical fertilizer, and manure on yields of wheat, Indian corn, and oats on various plots at Wooster, Ohio.

involved: cultivation (c); use of fertilizer (f); and crop rotation (r). The effects of these three factors are reflected in yields, whether they act singly or conjointly, as cultivation alone (c); cultivation and fertilizer (cf); cultivation and rotation (cr); and cultivation, fertilizer, and rotation (cfr).

Absolute and relative values of the fertilizer and rotation factors, in affecting yields, may be obtained as follows: Yield obtained from fertilizer in continual culture (cf) minus the yield obtained

in continual culture without fertilizer (cf — c) gives increase due to fertilizer (f); likewise, cr — c = r; cfr — cr = f; cfr — cf = r, and cfr — c = fr. In a given set of comparable results, it is reasonable to assume that the value of "c" is constant.

Effects of fertilizer and rotation. The beneficial effects of crop rotation do not counteract those of manures nor of commercial fertilizers. In fact, the effects of rotation are distinct, so that crop rotation does not in any sense take the place of or render unnecessary the use of manures and commercial fertilizers. The yields produced by fertilizer and rotation, when acting conjointly, may be more than twice as great as yields that may be obtained from the use of manure or fertilizer alone. These facts may be illustrated by 25-year average results obtained at Wooster, Ohio, with maize, oats, and wheat grown in a 5-year rotation of maize, oats, wheat, clover, and timothy.

The fertilizers used on the crops named included nitrate of soda, superphosphate, muriate of potash, and dried blood (50 pounds on wheat only) applied as a complete fertilizer, and barnyard manure. The quantities of fertilizing elements applied are given in the accompanying table:

QUANTITIES OF FERTILIZING ELEMENTS APPLIED TO CROPS GROWN IN A 5-YEAR ROTATION AT WOOSTER, OHIO, 1894-1918

(Ohio Agr. Expt. Sta. Bull. 336)

PLOTS	CROPS	QUANTITY OF MATERIALS APPLIED PER ACRE	NUTRIENT ELEMENTS (PER ACRE)		
			Nitrogen (N)	Phosphorus (P)	Potassium (K)
		Chemical fertilizer in continual culture:	*Pounds*	*Pounds*	*Pounds*
* 2, 3	Corn	335 pounds annually	25	7.7	26.5
	Oats	342.5 pounds annually	25	7.5	30.7
2	Wheat	430 pounds annually	25	11.2	41.0
		Chemical fertilizer in rotation:			
11	Corn	320 pounds annually	25	5.6	32.8
	Oats	320 pounds annually	25	5.6	32.8
	Wheat	430 pounds annually	25	11.2	41.0
		Manure in continual culture:			
* 5, 6	Corn	3.75 tons annually	33	6.9	21
	Wheat	3.75 tons annually	33	6.9	21
5	Oats	2.5 tons annually	22	4.5	14
		Manure in rotation:			
20	Corn	4 tons	35.2	7.4	22.4
	Oats		†	†	†
	Wheat	4 tons	35.2	7.4	22.4

* Average.
† Residual effect.

The results obtained from the use of these fertilizers and rotation, alone and conjointly, on the Wooster plots are shown in the table on p. 502 and in Figure 107.

Results obtained on wheat and barley at Rothamsted, England, and on cotton at Florence, S. C., are shown graphically in Figures 108 and 109.

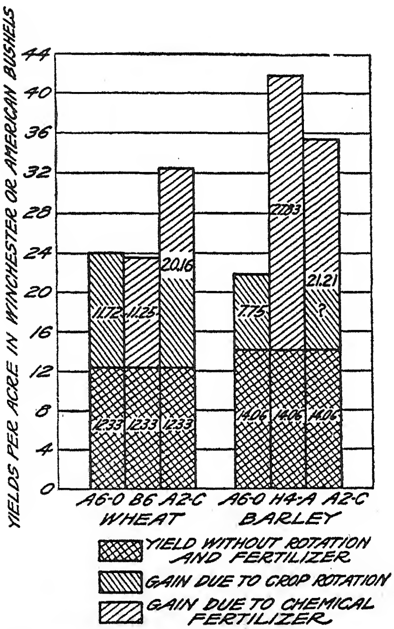

Fig. 108. Comparative effectiveness of crop rotation and complete chemical fertilizer on yields of wheat and barley on plots A6-O, B6, A2-C, and H4-A on Agdell, Broadbalk, and Hoos Fields, Rothamsted, England.

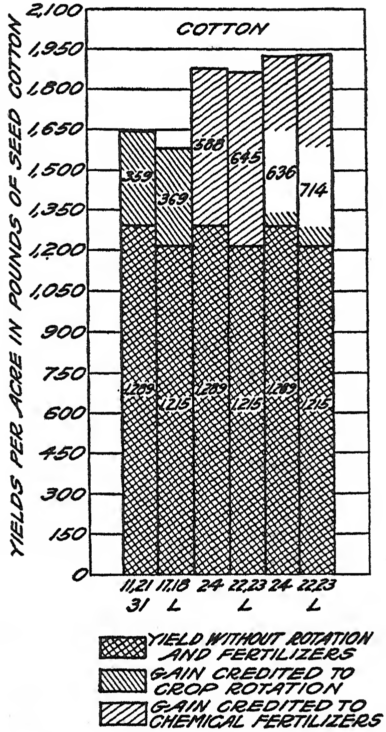

Fig. 109. Comparative effectiveness of crop rotation and complete chemical fertilizer on yields of seed cotton on limed (L) and unlimed plots at Florence, S. C. Full effects of each combined factor are not known.

Two values for rotation. In a given set of comparable crop-rotation results, it may be observed that rotation may be given two different values, expressed in terms of increases in yields. Different values arise according to whether rotation is "added" to cultivation only (c + r) or to cultivation and fertilizer (cf + r), as may be shown by the comparable results obtained on the Morrow Plots at Urbana, Ill. (table p. 502). The soil of these plots is of the Prairie class, originally well stocked with organic matter.

Single and Conjunct Effects of Fertilizers and Crop Rotation on Yields of Maize, Oats, and Wheat.

(Wooster, Ohio, 1894-1918)

Crop	Cultural Conditions	Average Yield per Acre	Increase Due to Fertilizer and Rotation (cf − c Singly and cr − c)	Conjunct Effects of Fertilizer and Crop Rotation: Theoretical Increase, the Sum of "f" and "r"	Actual Increase from Conjunct Effects of Fertilizer and Rotation (cfr − c)
		Bushels	*Bushels*	*Bushels*	*Bushels*
Maize	Cultivation only	16.88 (c) *	—	—	—
	Cultivation and complete fertilizer	35.88 (cf)	19.00 (f)	—	—
	Cultivation and rotation	27.24 (cr)	10.36 (r)	—	—
	Cultivation, fertilizer, and rotation	46.60 (cfr)	—	29.36	29.72 (fr)
	Cultivation only	13.33 (c)	—	—	—
	Cultivation and manure	30.53 (cf)	17.20 (f)	—	—
	Cultivation and rotation	27.62 (cr)	14.29 (r)	—	—
	Cultivation, manure, and rotation	42.81 (cfr)	—	31.49	29.48 (fr)
Oats	Cultivation only	20.86 (c)	—	—	—
	Cultivation and complete fertilizer	39.17 (cf)	18.31 (f)	—	—
	Cultivation and rotation	31.92 (cr)	11.06 (r)	—	—
	Cultivation, fertilizer, and rotation	51.24 (cfr)	—	29.37	30.38 (fr)
	Cultivation only	21.72 (c)	—	—	—
	Cultivation and manure	29.85 (cf)	8.13 (f)	—	—
	Cultivation and rotation	31.78 (cr)	10.06 (r)	—	—
	Cultivation, manure, and rotation	39.52 (cfr)	—	18.19	17.80 (fr)
Wheat	Cultivation only	7.77 (c)	—	—	—
	Cultivation and complete fertilizer	19.74 (cf)	11.97 (f)	—	—
	Cultivation and rotation	11.54 (cr)	3.77 (r)	—	—
	Cultivation, fertilizer, and rotation	28.12 (cfr)	—	15.74	20.35 (fr)
	Cultivation only	8.18 (c)	—	—	—
	Cultivation and manure	16.56 (cf)	8.38 (f)	—	—
	Cultivation and rotation	11.28 (cr)	3.10 (r)	—	—
	Cultivation, manure, and rotation	19.69 (cfr)	—	11.48	11.51 (fr)

* Productivity at the beginning of the experiment may be indicated by the average yields of the continual-culture plots for the first 5-year period, 1894-1898, as follows: maize, 29 bushels; oats, 27.8 bushels; wheat, 10.5 bushels.

Comparable Yields of Indian Corn Obtained on the Morrow Plots, Urbana, Ill.*

Year	Continual Cropping (Plot 3): Not Fertilized (c)	Continual Cropping (Plot 3): Fertilized with Manure, Phosphate, and Limestone (cf)	Three-Year Rotation (Corn, Oats, Clover, Plot 5): Not Fertilized (cr)	Three-Year Rotation (Corn, Oats, Clover, Plot 5): Fertilized with Manure, Phosphate, and Limestone (cfr)
	Bushels	*Bushels*	*Bushels*	*Bushels*
1904	21.5	17.1	55.3	72.7
1907	29.0	48.7	80.5	93.6
1910	35.9	54.6	58.6	83.3
1913	19.4	32.0	33.8	47.8
1916	40.0	10.8	27.8	40.6
1919	24.0	43.4	52.2	70.8
1922	24.6	39.4	49.2	65.3
1925	19.1	45.4	42.1	58.7
1928	18.8	32.4	44.2	70.4
1931	24.8	49.2	45.4	59.1
Average	25.7	37.3	48.9	66.2

* Data for last 2 years supplied by F. C. Bauer.

It may be observed that rotation "added" to cultivation (c + r) resulted in an increase of 23.2 bushels of corn (cr — c); and that rotation "added" to cultivation and fertilizer (cf + r) effected an increase of 28.9 bushels (cfr — cf). It may be noted, also, that fertilizer gave a greater increase in yield when applied in rotation (cr + f) than in continual culture (c + f), as indicated by increases of 17.3 and 11.6 bushels, respectively.

The question arises, What separate values may be given to the rotation and fertilizer factors in the yield obtained when they are combined (cfr), as in the average yield of 66.2 bushels? Rotation cannot be credited with all of 28.9 bushels, because this increase represents the effect of rotation plus an increase in the effectiveness of the fertilizer caused from "adding" rotation. It is reasonable to assume that the effectiveness of both factors (r and f) may be increased somewhat when the two factors are conjoined, as compared with their single effects (cr and cf).

And further, 17.3 bushels cannot be credited wholly to fertilizers, because this increase measures the effect of the fertilizer factor plus an increase in the effectiveness of the rotation that followed the adding of fertilizers. The sum of the single effects is 34.8 bushels of increase (r + f, or 23.2 + 11.6); their actual conjoint effects are expressed by an increase of 40.5 bushels (cfr — c). There is no way to determine how much of the difference of 5.7 bushels of increase should be credited to rotation and how much to fertilizers. We know that the increase effected by rotation, acting apart from fertilizer, is 23.2 bushels (cr — c). Accordingly, in the average yield of 66.2 (cfr), rotation may be evaluated at 23.2+ bushels, and fertilizer at 11.6+ bushels of increase. If the conjoint effects of rotation and fertilizer were not fully additive, rotation would then be evaluated 23.2— bushels of increase.

Lime increases value of rotation. In the study of crop-rotation values to which reference has been made, it was found that the beneficial effects of rotation were about 20 percent greater on soils that contained adequate lime than on acid soils, as based on yields of wheat, maize, oats, barley, cotton, and tobacco (Figs. 109 and 110).

Benefits of crop rotation. The beneficial effects of growing crops in rotation, some of which are not fully understood, are many. Among these benefits may be mentioned the following: Rotation aids in the control of weeds, insect pests, and certain crop dis-

eases; it conserves soil organic matter and nitrogen; improves the physical condition of soils; affords opportunity for soil improvement; distributes farm labor; systematizes farm operations; increases crop yields, and assures profitable returns.

Rotation aids in weed control. Growing small grains continually on the same land encourages the growth of weeds. This fact is well known. The weedy condition of the grain fields of England was one of the reasons that prompted Jethro Tull to work out some scheme whereby crops could be planted in rows to allow horse-hoeing (see Index). Rotation affords at least two opportunities for weed control. Weeds may be killed by intertillage of crops that are planted in rows, and they may be smothered by fast-growing crops.

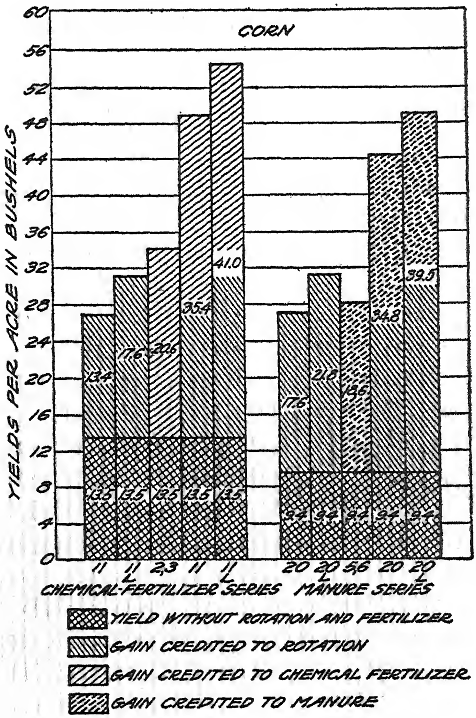

Fig. 110. Comparative effectiveness of crop rotation, complete chemical fertilizer, and manure on yields of Indian corn on limed (L) and unlimed plots at Wooster, Ohio.

Rotation for soil sanitation. Most of the insects and diseases that are injurious to crop plants are markedly limited as to the number of species on which the organisms concerned can live. Many of such insects and diseases are destructive to only one kind of crop. Continual growing of one kind of crop on the same land favors the development of these insects and diseases until ultimately the crop plants are unable to resist their attacks. Growing crops that are not attacked by some such insect or disease organism results in their destruction, because by so doing the life cycle of the injurious organism is broken. To

illustrate: Alfalfa-stem, tomato, and sugar-beet nematodes can be controlled most effectively by growing other crops; in some districts, European corn (maize) borer may be controlled by a shift to sugar beets; potato scab may be kept out of a field by growing the crop only once in a 4- or 5-year rotation; and development of root-knot of cotton and other crops may be prevented by growing the susceptible crop in a long rotation with immune crops, thereby starving out the wormlike pests.

Organic matter, nitrogen, and soil erosion. Continual growing of cultivated crops like maize and potatoes results in a most rapid destruction of soil organic matter (Ch. 28). In crop rotation, on the other hand, destruction of soil organic matter does not take place so rapidly. Moreover, the growing of clover and grasses aids materially in replenishing the supply of this important soil constituent. This fact has been emphasized by White (1931) in his study of the Jordan Soil-fertility Plots.

Attention has been called to the fact that bare soils lose large quantities of nitrogen as nitrates, and that this loss may be greatly reduced by growing crops. Commonly, soil nitrates are allowed to accumulate and suffer loss by leaching during late summer after some crops have been harvested, when the soils are left bare. In a well-regulated system of cropping and farm management, cowpeas, soybeans, and rye may be sown in such fields, and these crops may be used most advantageously not only as cover crops to conserve nitrogen, but also for green manure and for forage.

Soils in many cultivated fields on steep slopes lose much of their organic matter and nitrogen through soil erosion. Such losses may be greatly reduced by taking such fields out of cultivation and keeping them in grass or hay crops.

Rotation and tilth. Rapid destruction of soil organic matter through exhaustive cropping, coupled with no provision for replenishing it, soon results in poor physical condition of soils. Sandy soils lose their compactness, silt loams lose their crumby structure, and heavier-textured soils, devoid of organic matter, become hard and easily puddled when they are worked wet.

Growing grasses and clover in rotation with other crops greatly aids in the development and maintenance of good tilth. Furthermore, as different crops commonly call for different depths of seed bed, rotation of crops may lead to physical benefits which may result from varying the depth of plowing.

Rotation aids in maintaining soil fertility. Two important advantages which affect economic utilization of the soil reserves of the nutrient elements may be gained by growing different kinds of crops in rotation: (1) Alternating deep-rooted and shallow-rooted crop plants may effect the conservation of fertilizing elements, particularly when a deep-rooting crop, such as maize, follows a liberally fertilized shallow-rooting crop, as tobacco. (2) Another advantage lies in the fact that the "feeding power" and nutrient requirements of different crop plants vary widely. These two advantages aid materially in maintaining soil fertility and, on unfertilized land, particularly, tend to lengthen the productive period of soils.

Crop rotation affects favorably, directly and indirectly, all the other factors that determine soil fertility. If crops can be grown in succession so that the effects produced by one crop on the soil-fertility factors are favorable for the crop that follows, best results will be obtained. To accomplish this, proper sequence of crops, discovered by experiments and by practical experience, must be followed.

Rotation and soil improvement. In addition to the beneficial effects on soils and soil fertility that result from alternating crops, rotation affords opportunities for improving soils in other ways and for realizing greatest returns therefrom. For example, agricultural lime can be applied for the most responsive crops and at such time as to effect the best results with all crops of the rotation. Greatest immediate returns from the use of lime are commonly realized when it is applied for crops like clover and alfalfa. The soil changes brought about by the added lime and the increase in soil organic matter resulting from the better growth of clover invariably produce greater effects on succeeding crops than if lime were applied directly for these other crops.

On poor soils, adaptable crops may be grown in rotation with grass and clover in such manner as to make possible the frequent turning under of sod and green manure, thereby effecting much improvement in soils.

A well-regulated cropping plan may result in the gradual improvement in yields or it may greatly aid in maintaining a high degree of productivity. On the other hand, yields on long-cropped soils may gradually decline even though rotation and use of fertilizers may be practiced, but this proves that the rotation is not a

proper one, and that the fertilizer may not have been well selected or distributed. Commonly, the characteristics of such cropping systems are: (1) limited use of fertilizers and agricultural lime; (2) the growing of several intertilled and small-grain crops in succession; and (3) the growing of clover or grass at long intervals, that is, not often enough.

Crop rotation in farm economy. Crop rotation is an important factor in farm economy, affecting both labor and income. Di-

Fig. 111. Trends of yields of Indian corn on the Jordan Soil-fertility Plots. Maintenance of soil fertility depends generally on the combination of rotation of crops and use of fertilizers.

versity of crops favors distribution of farm labor and systematizing of farm operations, owing to the facts that the various crops are planted and harvested at different times, require different care, and encourage the keeping of more livestock. The practical results are better yields and assured returns.

Rotation alone not sufficient. Crop yields on soils several years removed from productive, virgin states indicate that, in general, highest yields and maintenance of soil fertility may be realized only when crop rotation and use of fertilizers are practiced together. Results of long-continued field tests have established this fact. The trend of the yields of Indian corn on the Jordan Soil-fertility Plots of Pennsylvania may be cited as typical (Fig. 111). The necessity of both fertilizer and rotation has greater significance when one considers the fact that the beneficial effects of rota-

tion are distinct from those of fertilizers. Rotation of crops and use of fertilizers may be regarded as complementary soil-fertility practices.

Rotation not always essential. Some crops respond more than others to the effects of rotation; perennial crops like bluegrass, redtop, timothy, and alfalfa may receive little or no benefit. Some crops, such as tobacco, cotton, potatoes, and turnips, may give much greater response to manure and fertilizers than to rotation on some soils, thus making it desirable, at least for a period of years, to grow them continually on the same land. For economic or soil reasons, or both, it may be desirable to grow certain crops on the same land year after year. This may be done with satisfactory results for a long period, provided the needs of the crop are supplied and especial care is exercised in keeping under control insect pests and crop diseases.

Many important crops—including wheat, Indian corn, and oats—seem to be adversely affected by continual cropping. Generally, however, such crops are grown in rotation, and continual cropping is the exception. The only reasons for continual cropping are favorable market conditions for crops like onions and tobacco, and high land values.

Principles of crop rotation. The principles that govern proper rotation of crops may be stated as follows:

1. Growing a row or intertilled crop, small grain, and a legume in rotation is a good farm practice, for yields are increased thereby.
2. Growing a crop that favorably affects the next following crop, as determined by tests and practical experience, is advantageous, for it increases the effectiveness of crop rotation.
3. Growing those crops that are best suited to both soil and climatic conditions is a basic factor in cropping, for such adaptation enhances the benefits of crop rotation.

Crop sequence. In general, proper succession of crops consists in growing cultivated crops, small grains, and legumes or grasses in the order named. Aside from the benefits thus derived and from control of crop pests and diseases, there are other effects produced by one crop on another that are not fully understood.

During the early years of the nineteenth century, De Candolle, a Swiss botanist, expressed the view that plant roots excreted certain substances, and that the different excrements may be nutritious for plants of different species and poisonous for plants of the same

species. Daubeny (Eng., 1845) and subsequent investigators have thoroughly tested this hypothesis, and have found no basis for it.

Another theory, advanced by Whitney (1906), was that substances may arise in the decomposition of organic matter left by one kind of plant which may prove to be toxic to plants of the same species but not necessarily to other plants; hence the explanation for the beneficial effects from alternate cropping. All attempts to establish this theory as fact have failed. On the contrary, evidence indicates that if any toxic substances do arise from decomposition of soil organic matter, they are made harmless through good drainage, proper tillage, and the presence of available calcium and magnesium (Ch. 17).

De Candolle and subsequent investigators have observed that plants of different species may be compatible or incompatible. For example, timothy and red clover may grow side by side apparently with mutual advantage. The same may be said of white clover and certain pasture grasses. Natural plant associations also suggest such beneficial or mutual relationships.

Sequence based on plant requirements. In their study of crop sequence, Hartwell and co-workers (1918-1919) obtained yields of from 13 to 17 bushels of onions to the acre following 2 years of cabbages, mangels, rutabagas, and buckwheat on a somewhat acid silt loam; 35 and 87 bushels after potatoes and rye; from 131 to 178 bushels after corn, millet, onions, oats, and red clover; from 240 to 314 bushels after squash, timothy, and alsike clover; and from 406 to 412 bushels following mixed timothy and redtop and redtop alone. After 2 years of miscellaneous cropping, they obtained from 4 to 10 bushels of buckwheat an acre following millet, grasses, corn, and clover; 13 and 15 bushels after buckwheat and oats; from 20 to 23 bushels after cabbages, mangels, onions, rye, squashes, and potatoes; and 34 bushels after rutabagas. Alsike clover yielded from 2.5 to 2.6 tons of hay an acre after clovers and carrots, from 4.16 to 4.33 tons after rye and redtop, and gave intermediate yields after other crops.

Investigating the causes for these variations in yields, Burgess (1924) concluded that the differences may be explained on the basis of soil reaction and plant nutrition. Onion plants, which are very sensitive to acid-soil conditions, grew poorly after mangels and on plots deficient in available calcium, magnesium, phosphorus, and potassium. Carrot plants are strong foragers for mineral

nutrients, thus indicating that they should not precede turnips. Indian corn and oats invariably yielded better after corn than after mangels.

Walster has reported the following average yields of spring wheat obtained in North Dakota on a Fargo clay for the period 1919-1926: 16.4 bushels after timothy or millet; 20.5 bushels after rye; 24.3 bushels after flax; 25.3 and 25.5 bushels after potatoes and red clover, respectively; and from 23.8 to 27.5 bushels after corn.

In his study of the effects of other crops on tobacco, Jones (1929) has observed that very few crops favorably affect the yield and quality of tobacco, and that a rotation of timothy, tobacco, and corn usually produces poor results which are associated with development of brown root rot on the tobacco. In Wisconsin, Thomas (1930) found that soils on which brown root rot had developed on tobacco invariably contained large quantities of cellulosic materials, and that such unfavorable conditions were overcome by providing tobacco plants with adequate supplies of quickly available nitrogen and phosphorus during early growth (Ch. 23).

In California, Conrad (1928-1932) found a close relationship between depression of soil nitrates by sorgo roots and by equivalent quantities of sucrose. Yields of barley were depressed progressively after millet, maize, broomcorn, and sorgo. Small grains following sorghums were benefited by applications of nitrogen fertilizers.

Onions usually yield poorly following tobacco; and yields of Indian corn are usually comparatively low after sugar beets, when no nitrogen fertilizer is used on the corn crop.

Crop sequence based on need for lime. The relation between onions and beets in rotation suggests a basis for crop sequence which is a modified form of one suggested by Liebig in 1840, namely, growing crops in descending order of their lime requirements. For examples: Alfalfa (heavily limed) followed by sugar beets and then barley; red clover followed by tobacco and wheat; alsike clover followed by maize and oats; and soybeans followed by potatoes and, in turn, by rye.

Crop sequence based on legumes. Legumes are the most important crops that may be grown in rotations. The effects produced on crops by the different legumes, however, may differ considerably. Wheat not only produces highest yields after alfalfa,

peas, and clover, but usually its protein content is notably increased as well. The same may be said of Indian corn.

In Alabama, Bailey and co-workers (1930) have reported results in which cowpeas and vetch (turned under), coupled with the use of phosphate and potash fertilizers, have maintained the yields of Indian corn at a level of slightly more than 19 bushels an acre for 34 years. Yields of cotton and Indian corn in a 3-year rotation (corn, cotton, oats), in which legumes were used as much as possible, were four times as great as those obtained in the same rotation, but without legumes.

Lyon (1925) has found that, under nitrogen-deficient conditions, incorporated residue of red clover produced results on succeeding crops superior to those with timothy and rye. In Tennessee, Mooers (1930) has obtained the following effects of preceding crops on burley tobacco:

Effect of Preceding Crops on Burley Tobacco

Preceding Crop	Number of Observations	Yield per Acre	Price Received per Pound	Gross Returns per Acre
		Pounds	*Cents*	*Dollars*
Red clover	22	1,574	29.3	461.18
Tobacco	23	1,459	26.6	388.09
Grass	60	1,480	25.7	380.36
Miscellaneous crops (Soybeans, corn, etc.)	38	1,351	26.3	355.31

Garner and co-workers (1925) and others have obtained similar results with tobacco, so far as yields are concerned, following clover, grass, and soybeans.

Evolution of modern crop rotation. The essential features of a proper rotation have resulted largely from the practical experience of husbandmen through the ages. As indicated by records, the evolutionary period covers more than 3,000 years, from about 1492 B.C. to about 1730-1738 A.D. During this time crop rotation passed through four distinct stages of development.

Resting cultivated lands marks the first stage of development. When primitive people adopted settled existence, cereals (small grains) became their principal sources of vegetable food. It was the common practice then to grow these crops continually on the same land until poor crops compelled the selection of new fields. Evidently primitive husbandmen soon discovered that resting a piece of exhaustively cropped land would renew its producing

power. This discovery gave rise to an early custom of abandoning cultivated lands, at more or less regular intervals, to the natural growth of rough and weedy herbage which provided scanty forage for domestic animals. Such great importance was attached to resting land one year in seven that the idea was incorporated into the Mosaic laws during the fourteenth century B.C. (Ch. 1).

Bare-fallowing, or naked-fallowing, marks the second stage in the evolution of crop rotation. The sabbatical land rest of the ancient Hebrews naturally favored the growth and dissemination of weeds, which compelled tillage or fallowing of reposed land during summer. Fallowing must have originated at a very early date, as most of the Roman writers on agriculture recommended this operation.

The ancient Romans included bare-fallowing in their triennial system of cropping which they introduced into all parts of the Empire. In this system a winter grain like wheat was followed by a spring-sown grain like barley which, in turn, was followed by naked-fallow. Two great advantages over repose husbandry were gained by this 3-year system: (1) it provided an effective means of getting rid of weeds; and (2) for a time at least, it made possible the production of more food per unit of land. This famous triennial cropping scheme of the Romans survived the Dark Ages (476-1300 A.D.) and was revived in Europe during the Renaissance (Ch. 1). It persisted in England during the eighteenth century in spite of thousands of enclosure acts, and was introduced into the New World. It still survives in districts of Europe and even in the United States.

Introduction of clover characterizes the third stage in the development of crop rotation. Improvement upon the fallow system of husbandry was suggested by the Carthaginians and Romans in their recognition of the value of alternating small grains with legumes and in growing leguminous crops for increasing the fruitfulness of the ground. The idea of growing clover and sown grasses in rotation with turnips and other crops was introduced into England from Flanders during the first half of the seventeenth century after Christ (Ch. 1). But its adoption there was met with strong resistance, owing to the firmly intrenched Roman three-field system. Jethro Tull (1733) suggested the prevalence of weeds as another objection to the adoption of this cropping plan (Ch. 1). In 1758, Hale (Eng.) referred to the growing of turnips

and other root crops in rotation with clover and sown grasses as the new husbandry which had the great advantage of producing two more crops (turnips and clover) in 6 years, as compared with the old English system. Later, turnips and clover were included in the famous Norfolk rotation which had come into prominence during the 1730's.

Writing about clover in 1676 as he had observed it in his visits to Flanders, John Worlidge (Eng.) said:

> This Grass hath born the name; and is esteemed the most principal of Grass, both for the great Improvement it brings by its prodigious Burthen, and by the excellencie of the Grass or Hay for Food for Cattle. . . . It hath also this Property, that after the growing of the *Clover-grass* three or four years, it will so frame the Earth, that it will be very fit for Corn again.

The introduction of clover and sown grasses into rotation ultimately did away with bare-fallowing in humid regions, owing to the fact that clover not only gives rest to the land but also enriches it at the same time. Moreover, it gives an extra crop in the cropping scheme.

Introduction of intertillage marks the fourth stage in the development of modern rotation of crops. For more than 9,000 years, up to nearly the middle of the eighteenth century, all seeds sown in the fields were broadcast by hand; this practice did not permit subsequent tillage. Cultivation of field crops after planting was introduced into systems of cropping in Western agriculture by Jethro Tull (Eng.) in 1730. This necessitated the planting of certain field crops in rows, and the invention of suitable implements for planting them in this manner. Turnips and other root crops soon became the intertilled crops.

Both row-planting and intercultivation were included in the Norfolk rotation, the first system of cropping that gave full expression of the principles of rotation. The fact that it took more than 3,000 years to work out the underlying principles of crop rotation illustrates how difficult it is sometimes, in spite of years of practical experience and creative thinking, to make a simple crude discovery a scientific practice.

The Norfolk rotation took the form of a standard 4-course system, including turnips, barley, clover, and wheat, grown in the order named. It was necessary that the crop planted in rows be

followed by a spring-sown grain (barley), because of the lateness in getting the root crop off the field. Barley is an ideal crop in which to seed clover and grass; and as Arthur Young (Eng., 1770) expressed it, "Wheat is ever the best after the best crops of clover."

General application of rotation principles. Although the methods of proper crop rotation previously given are based on the result of rotations as practiced in humid regions, it is believed that

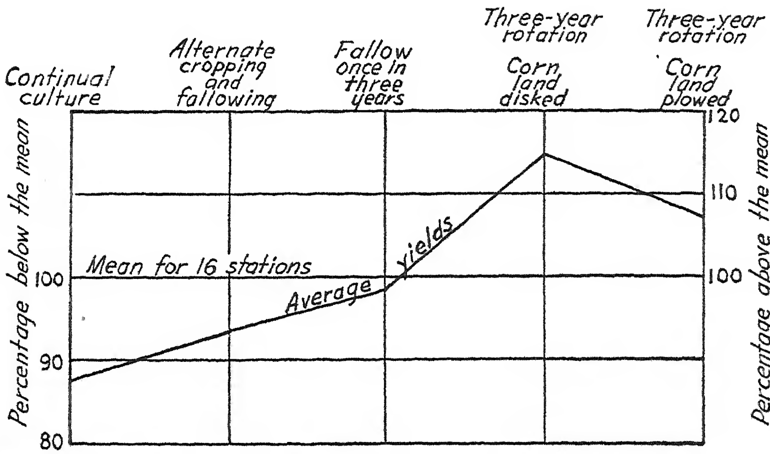

Fig. 112. Summary of 14-year crop-rotation tests under dry-farming conditions in western United States, based on yields of spring wheat, oats, and barley at 16 field stations in the Great Plains region. (After Chilcott.)

the principles stated have universal application. Chilcott (1931) has shown the importance of proper crop rotation in the dry-farming regions of the United States, in which the average annual rainfall varies from 12.36 to 28.51 inches, with an average of about 18 inches (Fig. 56). A summary of the results of his investigations, based on yields of spring wheat, oats, and barley at 16 field stations for an average period of 14¼ years, is shown graphically in Figure 112. He concluded that rotation is equally as important for the southern part of the Great Plains region as it is for the northern part.

From their investigations of crop rotation under irrigated conditions in western Nebraska, covering a period of 15 years, Scofield and Holden (1927) found that oats gave as good yields when

cropped continually as when grown in simple rotations; while potatoes, sugar beets, spring wheat, and Indian corn responded to proper rotation.

Twenty-year irrigation results at Logan, Utah, reported by Stewart and Pittman (1931), show that almost any rotation was beneficial to small grains, and was nearly as effective as manure for sugar beets. Sequence in cropping was found important for potatoes, alfalfa, Indian corn, and for sugar beets on nematode-infested land.

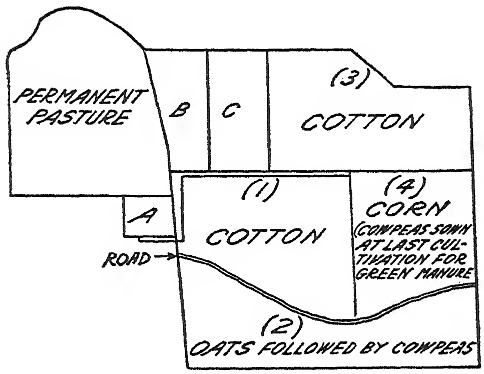

Fig. 113. A farm layout illustrating a plan for a 4-year rotation of cotton, oats, cotton, and Indian corn. A, Farm buildings, garden, etc. B and C, Sweet-potatoes, peanuts, or other crops.

The principles of crop rotation may be applied in a short 3-year system which includes a cultivated crop followed by small grain which, in turn, is followed by a legume: for example, Indian corn, followed by wheat, and then by clover. On the other hand, the principles may be applied in an 8-year or longer rotation, as may be determined by kind of crop, soil condition, and system of farm management or kind of farming.

Two or more rotations may be desirable on a given farm, in order to make possible better utilization of land. Inasmuch as some crops are particularly suited to certain soils, it is desirable to take advantage of these adaptations rather than to grow crops under conditions that are unfavorable to them. Moreover, some soils require different treatment than others in regard to improvement and maintenance of fertility. Farm economy is another important factor in establishing proper rotations (Figs. 113 and 114).

Factors that determine rotations. Several factors have to be considered in planning and executing proper rotations. These include (1) crops and livestock naturally and economically adapted to a given locality or district; (2) type of farming best suited to conditions; (3) most profitable combination of crops or of crops and livestock; (4) economic balance between crops and livestock;

(5) soil improvement and maintenance of soil fertility; and (6) crop sequence.

On many farms the cropping problem resolves itself into two parts: (1) growing of feed and cash crops in a manner, or in dif-

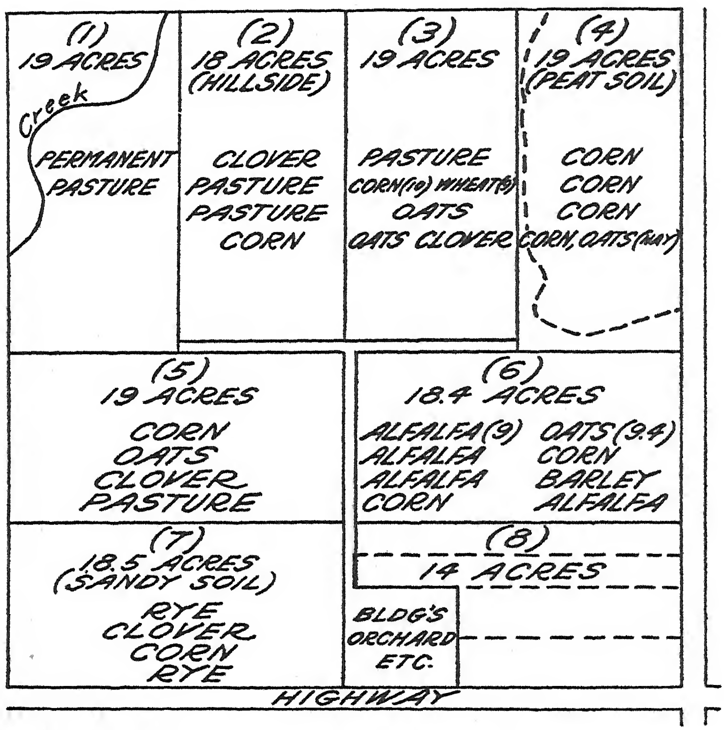

Fig. 114. Farm layout showing how soil and crop problems may be solved by proper crop rotation. Here the plan is to grow annually, in addition to a few acres of tomatoes and cabbages, about 38 acres of maize, 32 acres of hay, from 30 to 37 acres of small grains, and 18 or 19 acres of pasturage in rotation.

ferent rotations, best suited to local agricultural conditions; and (2) dovetailing, as it were, the different rotations so as to allow annually the acreage of each crop desired or required (Fig. 114).

Fixed v. flexible rotations. The possibility that changes may become desirable should be kept in mind when crop rotations are planned. A rotation that will allow of easy modification is preferred to one that does not have this characteristic of elasticity or flexibility. Accordingly, fields should be laid out in such man-

ner as to allow them to be conveniently thrown together or subdivided, and rotation or rotations should be adopted that will allow of considerable alteration in the kind or acreage, or both, of crops without necessitating complete redistribution of the fields into new "shifts." Thus, crop rotations may be of two classes, *fixed* and *flexible*.

A fixed rotation, a system of cropping in which the crops recur at regular intervals, requires a fixed number of years to complete. The rotation of Indian corn, wheat, oats, and clover is an example; also cotton, cotton, Indian corn, and oats (with legumes).

A flexible rotation is a plan of cropping in which the crops recur in definite order, but which is not limited to a fixed number of years: for example, alfalfa (2 to 5 years), Indian corn or potatoes (1 to 2 years), and small grains (1 to 2 years).

Fixed rotations, where they can be executed, may aid materially in simplifying field management. Generally, however, flexible rotations are desirable, because they allow easy modification when conditions call for changes in the cropping system. Changes in economic or market conditions, insect pests, crop diseases, weeds, drought, and soil-improvement plans may compel alterations in systems of cropping. According to Rew and Russell (Eng., 1920-1922), the 4-course Norfolk rotation, which for more than 100 years has been regarded as the standard cropping system in British agriculture, is not necessarily the best now. The Northumbrian farmers, particularly, are finding that they can obtain better results when the clover or grass mixture is left 2 years instead of 1, thus making it a 5-year rotation. In many places, however, the essential features of the Norfolk rotation prevail, particularly in Denmark.

Elasticity in crop rotation has been recognized as an important factor in successful soil management for so long that it may be regarded as a principle in farming economy. Very probably the farmers of Flanders practiced rotation elasticity in their husbandry as early as the Middle Ages, if not before or during Roman times. About 1600 A.D., English writers on husbandry referred to certain cropping ideas of the Flemish farmers—such as change of crops, adaptation of crops, and short and long rotations—as having been practiced by them from time immemorial.

Short v. long rotations. The length of rotation may vary from 2 to 12 years, determined by such factors as combination of crops,

crop sequence, length of time grass and certain leguminous crops are left down, soil conditions, pests, and soil-improvement plans. Under certain conditions, a 3-year rotation may give best results; under other conditions, a longer rotation may be desirable.

Inasmuch as legumes and grasses may be regarded as the renovating crops of rotations, the effectiveness of a rotation may depend largely on the length of time a perennial legume like alfalfa is grown and on the interval between these renovating crops. Lyon (1930) has reported results in which a rotation with only 1 year of red clover, but with peas planted with oats, and winter vetch with winter wheat, was as productive as a similar rotation with 2 years of red clover but no legume seeded with the small grains. Common errors in many cropping systems consist in growing too many cultivated and small-grain crops in the intervals between renovating crops and in growing two crops in succession that require much nitrogen. Some of these points are well illustrated by the average yields and annual values of crops grown in different rotations at Kingston, R. I., and at Wooster, Ohio.

COMPARATIVE PRODUCTIVITY OF CROP ROTATIONS
(20-Year Averages, 1893-1912, Kingston, R. I.)

Rotation * (Crops Grown in the Order Named)	Comparative Average Yields per Acre of Potatoes and Corn	Average † Annual Net Profit
	Bushels	*Dollars*
(C) Potatoes, rye and rowen, grass	Potatoes 237	14.26
(D) Potatoes, rye and rowen, grass, maize	Potatoes 234, corn 67	12.18
(E) Potatoes, rye and rowen, grass (2 yr.), maize	Potatoes 231, corn 60	12.11
(F) Potatoes, rye, grass (2 yr.), maize (No legume)	Potatoes 249, corn 59	11.66
(B) Potatoes, rye and rowen, grass (3 yr.), maize	Potatoes 260, corn 66	16.45

* All crops were grown each year, and like crops in each rotation were fertilized in like manner with complete fertilizers. Each plot received the same quantities of complete fertilizers during each 4-year period. Lime was applied on all plots at the rate of 1,000 pounds of CaO per acre once in 6 years. Stable manure (4 cords per acre) was applied only for corn in rotation D and on half of the plots of rotation B.

† For the period 1921-1929, with slight modifications in the rotations, the average yields of potatoes and corn were, respectively, as follows: C, 358, —; D, 368, 70; E, 320, 70; F, 332, 63; and B, 282, 69 bushels.

At Wooster all crops in all rotations are grown each year; and once in 4 years the soil (silt loam) receives 2 tons of limestone to the acre, 2 tons of stable manure, and 160 pounds of superphosphate (20-percent).

COMPARATIVE EFFECTIVENESS OF CROP ROTATIONS
(11-Year Averages, 1919-29, Wooster, Ohio)

Rotation (Crops Grown in Order Named)	Average Yields per Acre (Given in Order of Crops)	Average Annual Value of Crops
		Dollars
Maize and oats (seeded with sweetclover)	68.9 bu., 55.0 bu.	36.83
Maize and wheat (sweetclover)	67.4, 31.4 bu.	44.87
Maize, wheat, alfalfa (1 yr.)	80.7, 39.1 bu., 4,266 lb.	45.69
Maize, wheat, red clover	74.3, 36.0 bu., 3,673 lb.	39.70
Soybeans (seed), wheat, red clover	20.7, 37.3 bu., 3,644 lb.	31.98
Maize, oats, red clover	79.2, 61.5 bu., 3,934 lb.	34.56
Maize, soybeans (seed), wheat, red clover	75.7, 18.8, 30.3 bu., 2,794 lb.	34.22
Maize, oats, wheat, red clover	72.2, 63.9, 37.6 bu., 3,280 lb.	35.78
Maize, oats, red clover, wheat (sweetclover)	79.4, 61.8 bu., 3,455 lb., 39.5 bu.	37.74
Maize, maize, wheat, red clover	78.5, 61.9, 31.3 bu., 3,585 lb.	40.60
Maize, oats, wheat, red clover, timothy	77.1, 59.7, 37.2 bu., 3,723, 4,653 lb.	34.02
Maize, oats, alfalfa for 3 years	89.3, 66.8 bu., 4,618, 5,416, 5,771 lb.	39.28

Increasing productiveness of rotation. A cropping system may be made more productive by introducing extra renovating crops and by applying fertilizers to benefit certain crops directly and to favor the growth of clover. To illustrate:

(1)	(2)	(3)
Corn (maize)	Corn (manured)	Corn (manure and phosphate)
Oats	Oats	Oats (seeded with a legume for green manure)
Wheat	Wheat (land limed for clover)	Wheat (lime and phosphate)
Clover	Clover	Clover

Cultivation, rotation, and use of fertilizers. This chapter on crop rotation completes the discussion of 8 principal factors that determine soil fertility. When all conditions are properly met, or when all factors are allowed to act favorably, productive yields may be obtained as the result of the interaction of these important

factors. In the regulation and control of these several factors, three principal farm practices are involved: namely, cultivation, rotation of crops, and use of fertilizers (including lime). Each of these practices may be of almost equal importance in the establishment of permanent agriculture in any region or country.

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REVIEW QUESTIONS

1. Explain why crop rotation should be regarded as one of the factors that determine soil fertility. Illustrate.
2. What is the explanation of the beneficial effect of rotation on crop yields?
3. Illustrate with some local farm how crop rotation may aid in solving soil and cropping problems.
4. Can crop rotation alone maintain yields? Can organic matter alone? Can chemical fertilizers alone?
5. Discuss the principles of crop rotation. Why are these concepts called "fundamentals" and "principles"?
6. Sketch briefly the evolution of crop rotation.
7. In farm management, what factors should be considered in planning rotations?
8. What are the advantages of a flexible system of cropping? Illustrate.
9. Show how crop rotation may be evaluated.
10. Give an explanation of why corn (maize) usually yields poorly after sugar beets (see Index).
11. Discuss crop rotation in relation to sustained agriculture of a region or country.

CHAPTER 25

SOIL CONSERVATION

This chapter on soil conservation consists of two principal parts. The first part deals with basic things regarding soil erosion and soil conservation, with special reference to farm lands, under the heading "Soil Erosion." The second part deals also with erosion and conservation, but is considered from the point of view of watersheds, under the caption "Watershed Protection."

SOIL EROSION

It is clear that soil erosion cannot be considered a soil-fertility factor. It is rather a problem, one that came into existence when man began to draw directly upon the ground for the sustenance of life. Inasmuch as soils constitute the very foundation of agriculture, it should behoove man to see to it that soils remain in place, in order that he may continue to have sufficient suitable lands to till for his daily bread.

Geologic v. soil erosion. The surface of the ground has always been, and continually is, subjected to slow wearing-away action of rain water, winds, melting snows, and ice, of which run-off from precipitation is the most active agent. Winds, too, are active. Acting through long geological time, running waters, made more erosive by abrasive materials acquired from rocks, have eaten into uplifting rock formations and have ultimately worn down rugged hills and high mountains. This is *geologic erosion.*

Through the ages, geologic erosion, generally, did not proceed at so rapid a rate but that it allowed the action of certain natural constructive forces, which forces, among other results, caused the development of vegetation of various types, as determined largely by annual rainfall and temperature, the master factors. In time, the vegetation protected the ground surface against beating rains, moving water, and winds, thus allowing, in turn, the development of soils. As soils developed, they, too, were subjected to slow wearing-away action, hence *normal soil erosion,* caused mainly by surface run-off—the least on level areas and the most on steep slopes. But

when white man, through severe and careless land uses, destroyed the protective vegetation or caused it to deteriorate, he not only arrested the natural constructive forces but also aggravated natural destructive forces, as evidenced by such conditions as (a) denuded areas with more or less of the topsoils washed away or with only subsoils or with no soils left at all, (b) formerly productive lands dissected by erosion channels, and (c) destructively channeled alluvial valleys. The action of the destructive forces is reflected in *soil erosion,* which is *the accelerated removal of soil material by natural agents, mainly run-off, tending to land destruction* (Figs. 116-119).

Soil erosion proceeds at a much faster rate than soil formation and normal soil erosion, tending to soil ruination, hence the commonly used term *accelerated soil erosion.*

Tragedy of ancients. The past ages have witnessed the rise, domination, decadence, and final disappearance of one people after another. The countries inhabited by these vanquishd peoples reveal the tragedy of wasted soil resources, for example, the Mayan country of Yucatan, Babylonia, parts of Asia Minor, Greece, and northern Africa. In these modern times, land difficulties have been slowly creeping upon us for some time. Destructive soil erosion has already become a problem of state and national concern; its solution can be worked out only on the lands themselves. The tragedy of ancient peoples should warn us of the far-reaching, calamitous consequences of allowing wastage of soil resources.

Soil wastage not all. Besides the wastage of soil resources, there are other evils attending soil erosion—clogging of stream channels; excessive siltation of storage reservoirs and other irrigation works; burying of rich bottom lands by sand and gravelly erosion debris; rapid concentration of flood waters through erosion channels; increased surface run-off at the expense of natural replenishment of ground-water supplies; the spreading of unpalatable plants on grazing lands; invasion of semidesert grasslands by desert shrubs; killing of fish and game by muddy waters; impairment of public health by choking dust storms; retarding of traffic and commerce; and retrogression of agricultural communities.

Types of water erosion. There are three types of erosion by run-off: sheet erosion, rill erosion, and gully erosion. Sheet erosion and rill erosion are not necessarily prerequisites to gullying.

Sheet erosion is the accelerated removal of soil material by surface run-off more or less evenly over a given area.

Rill erosion is the accelerated removal of soil material from land areas in very narrow strips by surface run-off flowing in very narrow channels an inch or more deep with vertical walls.

Gully erosion is the accelerated removal of soil material by concentrated run-off with strong cutting and transporting power, forming channels of considerable size on land areas.

Wind erosion. By wind erosion is meant the accelerated removal

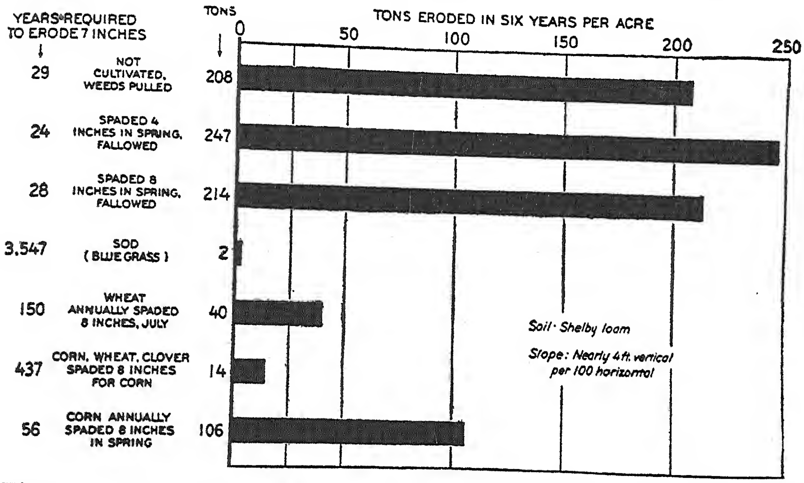

Fig. 115. Soil erosion of a loam soil in relation to degree of slope and agricultural practices, based on a 3.68-percent slope and 90-foot length of slope at Columbia, Mo. (After Baker.)

of soil material from land areas by winds. This form of soil erosion is common in dry and subhumid regions. Wind-borne soil material may be carried great distances, and wind-blown sand may be heaped into immense hills or dunes.

Factors of erosion. Factors that affect the rate of deterioration of farm, range, and forest lands through erosion include vegetation, character and distribution of rainfall, degree and length of slope (Fig. 115), climate, character of soil, and agricultural practice.

Farm practices conducive to erosion. Among agricultural practices that have induced soil erosion may be mentioned the following: plowing and tilling up and down slopes (Fig. 119), cropping of steep slopes, one-crop farming (Fig. 115), neglect of shallow surface drainageways (Fig. 121), overgrazing, exhaustive cropping, and abuse of timberlands and woodlands (see Fig. 118, also p. 125).

Soil conservation. Various countries have established soil-conservation policies. In the United States, for example, the Soil Erosion Service (Soil Conservation Service, 1935) was established in 1933, with a view to husbanding the soil resources for long-time or permanent use, especially for agricultural uses. To conserve soil and other natural resources does not mean to refrain from human uses, but rather to use them understandingly and with due regard

Fig. 116. Gully erosion on an area of soil classed as *Knox silt loam* (developed from loess).

for nature, in recognition of sustained yield as a prerequisite in the economy of a strong human society.

Soil-conservation measures. In general, soil conservation may be effected by (a) using vegetation as much as possible to protect fields and other areas against erosion, (b) by installing minor engineering structures to aid in retarding run-off and in revegetating or establishing protective vegetation where necessary, and (c) by using soil-improvement materials, where necessary and feasible, to aid in growing or establishing protective vegetation in critical areas. Specifically, approved soil-conservation measures include the following:

Strip cropping, the growing of crops like grasses and small grains, alternated with row crops, on the contour (Fig. 120), to increase infiltration. Narrower strips and more grass on steep slopes.

Crop rotation in contour strips, including cover crops, to minimize water and wind erosion in farm cropping programs (Fig. 122).

Terracing with diversion ditches, to lead excess water across the slopes at low velocity and thereby prevent gully formation.

Grassed surface-runs or shallow drainageways, to prevent gullying (p. 260); also called *meadow strips.*

Improved pastures, to allow grazing use while at the same time holding the soils in place by grass and binding sod.

Contour furrowing and listing, also stubble mulching, on grazed fields or areas, to retard surface run-off and increase infiltration.

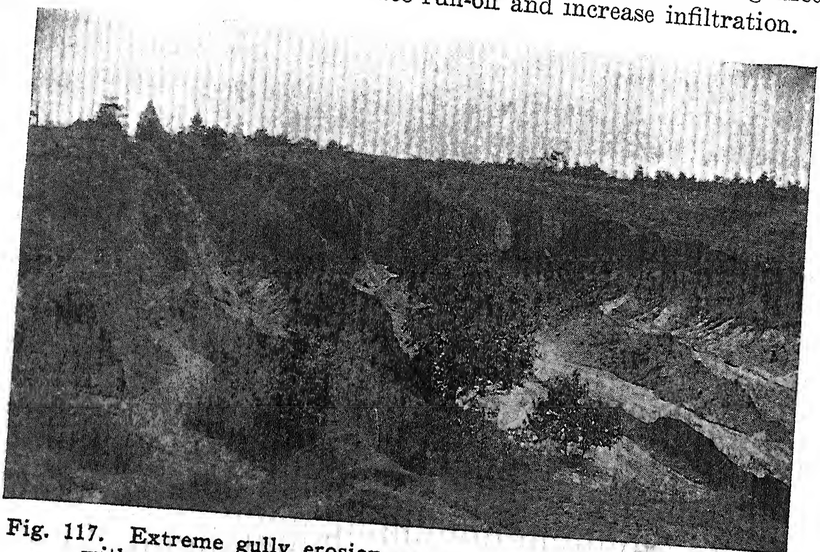

Fig. 117. Extreme gully erosion on an area of silt loam underlain with sandy coastal-plain material. Formerly corn land.

Stream-bank improvement, to minimize bank cutting and floods, by jetties, revetments, revegetation (Fig. 123), and alignment.

Minor structures, such as head-cut drops in active gullies (Fig. 124), diversions with water spreaders, gully stabilizers, and stream-bottom fencing, especially on range and forest lands, for retarding run-off, preventing further gullying, and aiding revegetation.

Dikes and culverts for the protection of highways and farming areas against damaging run-off and flood waters.

Side-wash improvement on range and forest lands, accomplished through channeling and the use of smaller detention dams, for controlling water flow, to prevent flood damages.

Protected timberlands and woodlands on farm and range lands, also land retirement, in order to favor remedial measures and to

allow improvement of ground cover, and thereby lengthen the service life of any structures built for flood-control or land-improvement purposes.

Combined measures. One measure supplemented by another or others may be necessary, as is usually the case.

Community action. Individual effort to control soil erosion is not likely to accomplish very much, inasmuch as this problem does not recognize fence lines. What one man fails to do may bring to naught the efforts of his neighbors; thus the need for a mechanism whereby land owners of a watershed or other natural land-use area may organize for concerted action and mutual protection in combating soil erosion. In the United States, this need has been met by State legislative action in the form of a standard statute called the Standard State Soil Conservation District Law, beginning in 1937.

WATERSHED PROTECTION

The problems of soil erosion, run-off control, and soil conservation may be viewed in a broad way, in relation to human welfare, when considered from the point of view of watersheds, or drainage basins. In such consideration, attention centers on *watershed values*, which values are based on the function of watershed lands when so managed as to mitigate or prevent soil erosion, sedimentation, and flood damages, and to make secure the supplies of usable water for irrigation and other purposes.

Watersheds under natural conditions. Nature clothed the watersheds with vegetation of various types, such as forest, woodland, brush or chaparral, prairie grassland, savanna, pampa, veld, steppe, plains grassland, and shrub. In humid regions, forests and certain grasslands generally characterized the uplands; in arid, semiarid, and subhumid regions, vegetation of various types developed (p. 124). The native vegetation constituted, for the most part, protective ground cover, as evidenced by developed soils. Soils with well-developed features occur on all parts of a watershed, even in dry regions. On desert areas, vegetation functioned as a minor factor; while on lands other than deserts, vegetation played a most important role.

Ordinarily under natural conditions, the stream channels were stabilized, the drainage waters ran clear, and generally, fish inhabited the headwater and permanent streams of dry regions. How-

ever, recurrent floods were normal occurrences, and there also occurred occasional great flood flows, as evidenced by flood plains.

Results of modern land uses. In the course of time, white men encroached upon the alluvial flood plains, built cities and developed farms; and used uplands for farming and grazing. Forests were exploited. Modern land uses resulted in the destruction of the formerly protective ground cover, or it deteriorated because of care-

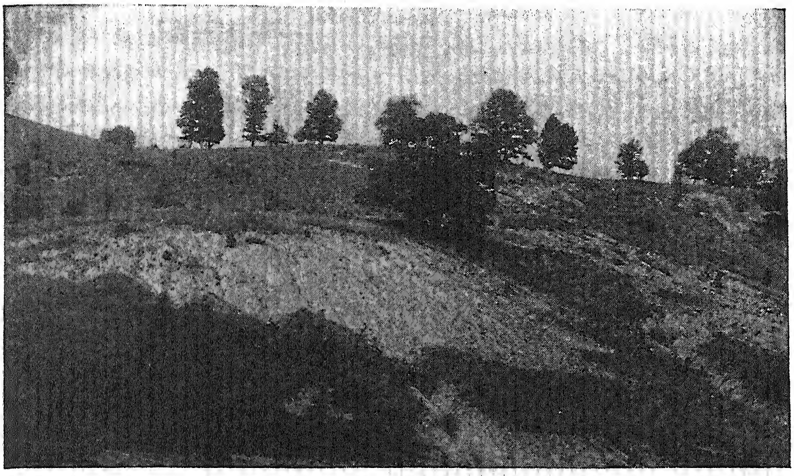

Fig. 118. Destructive erosion on a slope, unwisely cleared, in the Blue Ridge part of the Appalachian Mountains.

less land uses. In consequence, stream flows have become detritus carrying, excessive siltation is in progress everywhere, and white men now experience recurrent destructive floods, many of which occur at shorter intervals and with increasing crests.

The hydrologic cycle. Watershed values involve the *hydrologic cycle,* which cycle implies the movements of water on the surface of the earth, its utilization and transpiration by vegetation, transformation into vapor and clouds, and its subsequent precipitation upon the earth. Whether land uses result in the preservation or deterioration of watershed lands depends on the consideration given to the hydrologic cycle, which cycle is governed by an ever operating natural law.

What becomes of rain. Several things happen during an effective rain. At first there is usually a beginning rainfall of low intensity (*initial rain*), when the ground rainfall, or the rainfall

that actually reaches the ground surface, readily sinks into the ground. As the storm continues and the rainfall intensity exceeds the infiltration rate, the ground surface begins to divide the ground rainfall into two parts: (a) that which sinks into the ground and (b) that which concentrates on the surface (*rainfall excess*) and produces surface run-off, which is the water that reaches surface drainage channels by the overland route.

Fig. 119. Erosion between rows of cotton that run up and down the slope.

Water that sinks into the ground, after it satisfies the moisture capacity of the zone of aëration, follows subsurface routes, first percolating to ground water or to saturated underground zones. Further underground movement is toward surface drainage channels, where the water appears as springs or seeps and becomes *ground-water run-off* or *subsurface run-off*. Although surface and ground-water run-offs make up the total run-off, it is the ground-water run-off that determines the permanent flow of streams. In mountainous watersheds, the discharge of subsurface water into drainage channels during heavy rains may occur at a much greater rate and volume than the usual discharge of ground water, or effluent seepage.

Infiltration and run-off. If all the ground rainfall sinks into the ground, obviously there can be no surface run-off. And, conversely,

the less the infiltration rate during a heavy storm, the greater the proportion of the rainfall that disappears as surface run-off. Whether there is surface run-off and consequent soil erosion is determined by such factors as character of rainfall, surface relief, vegetation, character of soil, and land treatment. As regards the relation between infiltration and surface run-off, there are wide differences, other conditions being equal, between the results of short-

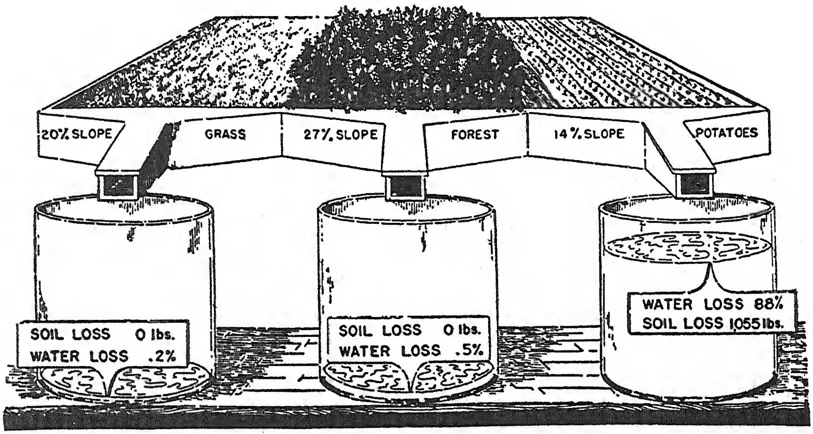

Fig. 120. Principle of soil erosion illustrated: When destruction of protective vegetation results in rapid run-off from the exposed soil, accelerated erosion is the inevitable consequence.

duration rains of high intensity and prolonged rains of low intensity. There are also wide differences between steep slopes and level lands, between long and short slopes, surface without vegetation and ground surface with protective cover, and between fields plowed or cultivated up and down the slope and fields that are plowed on the contour, terraced, and strip cropped.

When several factors operate in contributing to surface run-off—such as cloudbursts, hilly lands, and extensive denuded areas of easily erodible soils—the results may be devastating flash floods, destructive soil erosion, and excessive siltation of stream channels, lakes, and irrigation works. On the other hand, when other factors operate in contributing to infiltration and retardation of run-off—as protective vegetation and permeable soils—the results usually are increased infiltration and run-off with minimum silt. Further, favorable infiltration would set into action certain natural forces that would operate to the improvement of watershed lands.

Quantitative concepts. If a watershed receives an average annual rainfall of 30 inches, roughly, each acre receives about 3,000 tons of water, which is equivalent to a total of 30 acre-inches or 2.5 acre-feet. In the course of the year, all this disappears, by evaporation from the ground surface and transpiration through vegetation, as surface run-off, and through infiltration as ground-

Fig. 121. Reclaiming a gully through the use of soil-saving pole dams.

water run-off. It has been determined that in humid regions about half the annual rainfall may be accounted for in stream flow; the rest is lost. In arid, semiarid, and subhumid areas, with average annual rainfalls ranging from 10 to 25 inches, the relative annual losses may be as great as 85 and more percent of the total annual rainfalls. Incidentally, in arid-semiarid countries the water that is actually used for irrigation may represent a very low percentage of the annual rainfall of the drainage basin concerned. In Lower Egypt, for example, the water used for irrigation represents only about 3 percent of the annual rainfall over the Nile drainage basin. This emphasizes the importance of water conservation in arid-semiarid regions.

Damaging floods. Although much of the rain that falls upon watersheds is lost and hence does not appear as stream flow, recurrent floods are normal occurrences, caused by summer cloudbursts which cover comparatively small areas, by great storms of wide distribution, or by heavy rains with melting snows. Inasmuch as white men have appropriated to their uses the alluvial flood plains and

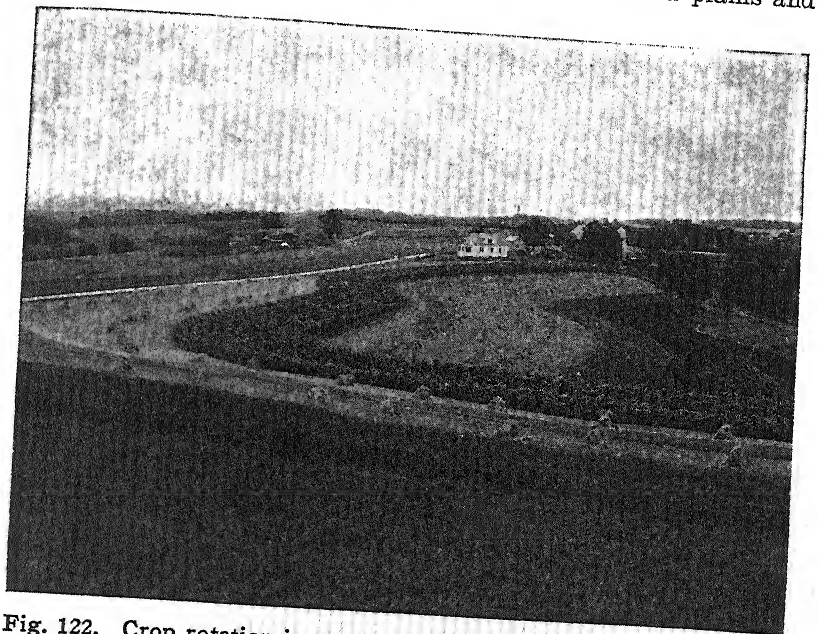

Fig. 122. **Crop rotation in contour strips, in order to minimize water erosion and wind erosion. (S.C.S.)**

bottom lands along streams, which had been used by the streams for centuries in dispersing their flood waters, floods may be expected at greater or lesser intervals for all time to come. Some floods are great inundations which gradually develop to peaks and then gradually recede; others are heavy flash flows which result from downpours on denuded hilly lands, as in southwestern United States. The damages caused by floods increase with developments.

Great floods. The greatest American flood on record occurred in the Ohio-Mississippi Valley in January 1937, in which about one million people were made homeless, and damages amounted to hundreds of millions of dollars. Other great floods include the New England flood of 1936, in which the worst damages were experienced

in 300 years, following white settlement; the New York State flood of 1935; the Ohio River flood of 1936; the major Texas flood of 1935; the Los Angeles flood of March 2, 1938; and others in various parts of the United States and the world.

Great rainstorms. It may be of interest to note, in connection with floods, what great rainstorms are like, as indicated by the following rainfall intensities, compiled from records: rainfalls of 1 to

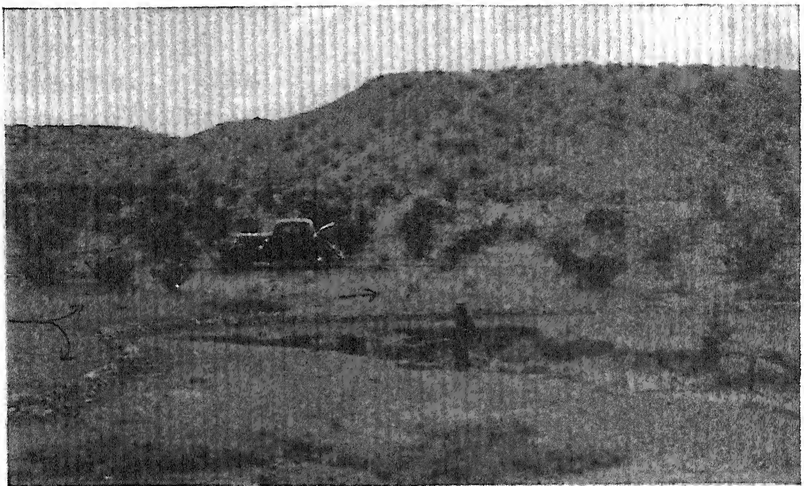

Fig. 123. Diversion and spreaders not only stop further gullying but also aid in the rehabilitation of range lands. (S.C.S.)

1.9 inches in 5 minutes; 1.4 to 1.9 inches in 10 minutes; 2.0 to 3.9 inches in 15 minutes; 2.9 to 9.2 inches in 30 minutes; 4.3 to 6.9 inches in 1 hour; and 20.1 to 23 or more inches of rainfall in 24 hours. Common results of torrential rains include much surface run-off and flooding, destructive soil erosion, and heavy flood damages.

Flood-control legislation. In June 1936, the Congress of the United States, in order to conserve human resources, passed the Omnibus Flood Control Act, thereby establishing a Federal policy as regards flood control for the country at large, taking into consideration not only the main streams and waterways but also whole watersheds and all the drainage basins of the country. The act places upon the War Department the responsibility for the improvement of streams and waterways through "downstream" structures like large dams, reservoirs, and dikes; and places upon the Depart-

ment of Agriculture the responsibility for necessary "upstream" measures, on the lands where flood flows originate, for run-off and water-flow retardation and prevention of soil erosion, in aid of flood control. The act implies co-operation between the War Department and the Department of Agriculture, also between various bureaus of the Department of Agriculture. It calls for preliminary examinations to determine whether surveys for flood-control purposes are warranted, and, in turn, watershed surveys to determine remedial measures. Under the terms of the act, the propriety of

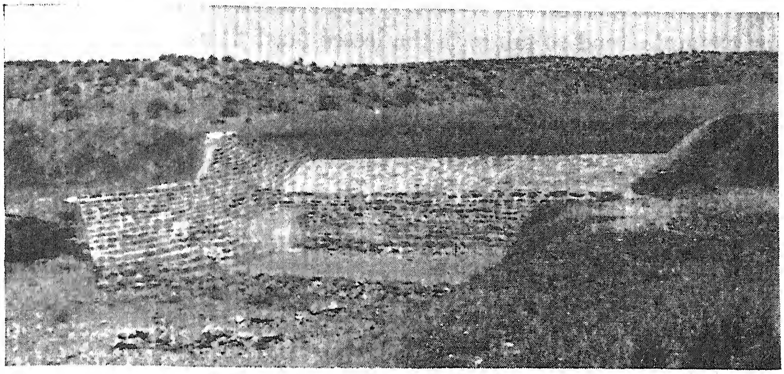

Fig. 124. A rubble-masonry, head-cut drop designed to carry a flow of 4,000 cubic feet per second, to stop a destructive gully which was advancing up a valuable meadow. (S.C.S.)

watershed treatment for any area is to be judged largely by the ratio of benefits to costs.

Measures for watershed improvement. Under the flood-control act, upstream measures for the retardation of run-off and stream flow and for the prevention of soil erosion—land-use adjustments supplemented by minor engineering structures—may be similar to those called for in soil conservation in general, except that watershed improvement calls for the co-ordination of the necessary measures with a view to preventing or lessening the aggregation of flood waters in destructive volume. Among various measures, protective vegetation is recognized as of primary importance.

Vegetation and floods. Although, ordinarily, protective ground cover is a potent factor in the control of surface run-off, it has limitations when great or unusual rainstorms occur. German foresters have established the fact that a fully protective forest and accompanying high infiltration afforded by forest litter may not

prevent floods. In explanation: A general rain of low intensity may thoroughly saturate the soil mantle of a watershed, and by high ground-water run-off may greatly augment the stream flow. A heavy, widespread storm, which may follow shortly, will not only add to the infiltering water which already augments the ground-water run-off but may also contribute directly and liberally to surface run-off. Under such circumstances an unusual flood flow may result.

Vegetation and conservation. Even though protective vegetation may lose its influence in heavy, long-continued rainfalls, forests, for example, tend to mitigate the lesser flood flows. According to the German foresters, the greatest value of forests during all rainstorms is in holding the soils in place, and hence in lessening soil erosion. These conclusions also hold for types of protective vegetation other than forests.

A striking demonstration of the influence of protective forest cover in controlling run-off is a comparison of flows from Pickets and San Dimas Canyons, which open into fertile valleys of southern California, on January 1, 1934. The previous year fire had destroyed the forest cover on 5,000 acres in the former canyon; no fire occurred in the latter. Because of a heavy rainstorm, which covered both canyons alike, a severe flood from Pickets Canyon killed 34 persons and wrecked 200 homes. There was no flood from San Dimas Canyon.

It is conceded that vegetation, especially in headwaters and critical areas, by greatly retarding surface run-off and aiding infiltration, effects more even and continued flow of streams. In arid-semiarid regions, it is reasonable to assume that the maximum delivery of usable water to meet human needs can be realized only when watershed conditions as regards protective vegetation approach those that existed under natural conditions. This would also mean, in the dry regions, the preservation of human resources.

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REVIEW QUESTIONS

1. Why is soil erosion not a soil-fertility factor?
2. Compare geologic erosion with normal soil erosion.
3. Compare soil erosion and accelerated soil erosion.
4. What warning comes to us from some ancient peoples?
5. What are the evils attending soil erosion?
6. Compare water erosion and wind erosion.
7. Discuss factors of soil erosion. Discuss agricultural practices.
8. What is the meaning of soil conservation?
9. Discuss soil-conservation measures, general, specific.
10. Why is there legislative action for soil conservation?
11. Make clear the meaning of watershed values.
12. Describe humid- and dry-region watersheds; natural conditions.
13. Discuss modern land uses and consequences.
14. Discuss the hydrologic cycle in relation to watersheds.
15. What factors favor surface run-off? Ground-water run-off?
16. Discuss rainfall in relation to soil erosion and floods.
17. What are the advantages of national flood-control legislation?
18. Describe some watershed-improvement measures.
19. Discuss the value of vegetation in erosion and run-off control.
20. Discuss delivery of usable water in a dry region.

CHAPTER 26

DETERMINING THE NEED FOR FERTILIZERS

An important problem in economic crop production is how to determine the need for fertilizers. The problem is a complicated one, because it involves many different crops and soil conditions. Although the requirements of a particular kind of crop plant in regard to nutrients, form of nitrogen, and environmental conditions may be fully understood, there remains the question of whether that crop will be able to obtain the nutrients it needs for profitable yields from the soil on which it may be planted. The problem is further complicated by weather and other conditions during the growing period.

When yields are unsatisfactory, even though seasonal and other conditions have been favorable, one may conclude that some kind of fertilizer might have been beneficial. But such a judgment at harvest time avails nothing, except that it may lead to the use of some kind of fertilizer the next season. The practical problem is to know beforehand or at planting time the kind and quantity of fertilizer to use for a given crop on a given soil in order to obtain, under normal conditions, satisfactory yields. Many schemes, based on chemical and biological principles, have been devised with a view to finding some way to acquire this useful knowledge. Some of these schemes have been designed to determine the need of different crops for fertilizers relative to certain distinguishing soil characteristics, whereas others have been designed to determine such needs regardless of the type of soil.

Native vegetation a criterion. Noting the character of native vegetation is the oldest means for judging the potential fruitfulness of the ground. Cato's attempt, more than 21 centuries ago, to classify agricultural lands according to plant growth suggests that primitive husbandmen learned to select fruitful ground on the basis of tree growth at a very early date (Ch. 1). The character of native vegetation still has value in judging agricultural lands (Ch. 9). In general, poor growth on cultivated lands, when mois-

ture is adequate, indicates the need for soil improvement and for fertilizers.

Analysis of plant ash. Relationship between the chemical composition of the ashes of plants and the nature of the soils on which they grew was first observed during the closing years of the eighteenth and the opening years of the nineteenth centuries, when chemists began to study the elemental composition of substances. De Saussure (1804), a Swiss naturalist, showed that plant ashes, which he found to consist mainly of alkalies and phosphates, were not constant in their composition, but varied with the character of soil and age and kind of plant (Ch. 1). Later, much work was done along this line by Sprengel (Ger., 1830-1840), Boussingault, Liebig, and Lawes and Gilbert.

In connection with field tests that he initiated in 1834, Boussingault analyzed the manure he used and the plants that were grown for carbon, nitrogen, and mineral matter, and worked out a balance sheet of these constituents; in this way he was able to show differences due to contributions from the air, rain water, and the soil. On analyses of the ashes of crop plants, Liebig based his estimation of their mineral requirements. Lawes and Gilbert, following the establishment of the Rothamsted Experimental Station in 1843, did much ash-analysis work, in which they found that with suitable indicators, plant-ash analyses could be used to determine the need for fertilizers—for example, Swedish turnips (rutabagas) for phosphate, mangels for potash, and straw of barley for both phosphate and potash fertilizers.

Generally, in the light of modern research, ash analyses cannot be relied upon to indicate the need for fertilizers, although agronomists and agricultural chemists hold that the composition of the ash of crop plants may be used as an aid in explaining unproductive spots in certain soil areas and in determining some deficiencies of soils of certain districts and even of extensive areas. The relation of iodine content of food and feed crops to the iodine content of soils, on the one hand, and to the health of humans and domestic animals, on the other, may be cited as an example.

Total chemical analyses of soils. Relationship between total chemical analyses of soils and soil fertility was first thought of by Sir Humphry Davy (Eng.) during the early years of the nineteenth century. In his day, Lavoisier (Fr., 1777) overthrew the phlogistic doctrine, involving the Greek Elements of Water and

Air and Earth, that had dominated chemical thought for more than 100 years after chemistry was placed on a scientific foundation (Ch 1). He experienced also that change of chemical thought which urged investigators to begin search for the structural elemental units, in which they discovered that Nature exhibited a fairly numerous collection of different elements of which earthy substances are composed.

Thus when Davy was requested by the board of agriculture, in 1802, to direct his attention, chemically, to problems of agriculture, it was quite natural that the chemical thought of his day should suggest to him the idea that probably the productivity of certain soils could be explained on the basis of their chemical analyses; this he attempted to do.

The value of chemical analysis of soils in soil-fertility studies was emphasized in 1840, when Liebig inferred that plants absorbed simple substances and converted them into complex organic compounds. At first Liebig valued chemical analysis of soils rather highly, but later (1863) he concluded that it rarely gave a correct standard for measuring the fertility or infertility of different soils, because, to be effective, the nutrient elements must be readily available, a form or condition that total chemical analyses could reveal only imperfectly. The same opinion was held by Ville (Fr., 1863) and Boussingault (Fr., 1865). The latter scientist suggested that mechanical analyses of soils might be of greater value. Experience at Rothamsted taught Lawes and Gilbert that soil analyses had little or no value in soil-fertility work.

Occasionally soils are found which, by total chemical analysis, may show deficiencies of certain nutrient elements.

Although attempts have been made to revive interest in *total* chemical analysis of soils as a basis for determining potential soil productivity and proper soil-management practices, the theory is no longer held scientifically, and it does not afford a promising field for inquiry. There is, nevertheless, a value to be attached to total chemical analyses of soils, because they aid in revealing the chemical nature of the soils. The value of soil analysis lies within a limited sphere which includes comparison of soils regarding their chemical constitution, discovery of relationships between chemical composition and physical properties of soils, and the tracing of chemical processes that are involved in soil genesis.

Chemical availability tests. The early recognition of the importance of the phenomenon of availability of the nutrient elements directed the attention of investigators to devising chemical methods that would give some measure of the condition of availability in which the major nutrient elements occur in soils or to determine whether crops would be able to obtain their nutrient requirements from different soils. Thus the emphasis was shifted from chemical composition of soils to the action of plant roots, or from the *total quantity* of the nutrient elements to the *fractional* or *available* portions.

Dyer's citric acid method was finally developed by Dyer (Eng.) in 1894. He proposed the use of a 1-percent citric acid solution as a means for measuring the availability of soil phosphorus and potassium, based on his study of the root action and the acidity of root sap of plants of more than 100 species. By this method he was able to approximate rather closely the comparative productivity of the soils of the Rothamsted experimental plots.

In this inquiry, subsequent investigators have worked with dilute solutions of oxalic, acetic, nitric, tartaric, and other acids. Dyer's citric acid method is still used in some European countries, particularly in Germany. In the United States, a 0.2-normal, or N/5, nitric acid method has proved to be very satisfactory.

Strong-acid digestion of soil materials for measuring the quantities of "zeolitically held" nutrient elements has been proposed for determining the availability of mineral nutrients on a strictly chemical basis. From their work with weak solvents, soil chemists, in the course of time, developed a conception of soil mineral nutrients which placed them in the following classes: (1) nutrients dissolved in the soil solutions, and therefore accessible to plants; (2) elements contained in so-called "zeolitic" compounds or poorly weathered and secondary mineral particles; and (3) elements that are contained in particles of primary minerals, and hence are inaccessible to plants.

It was thought that the mineral nutrients of the second class were also available to plants, and it seemed doubtful whether weak acids could extract them. Accordingly, methods were developed that involved the use of stronger acids. Of the methods proposed, the American Association of Official Agricultural Chemists has adopted the one that makes use of hydrochloric acid with specific gravity of 1.115, which was developed by Hilgard (1873).

Percolation and chemical-equilibrium methods have also been devised to take the place of acid-digestion methods, particularly in work with phosphorus. The first method consists in allowing solvents to percolate through soil material and carry out whatever substances are dissolved, thus avoiding chemical equilibrium in regard to the action of the acid. Percolation enables a continuous supply of fresh and unchanged solvent to act, thereby allowing the reaction to go in one direction toward completion. The second-named method consists in shaking soil materials with solvents for a certain length of time, in obtaining soil extracts.

From a comparative study of percolation and chemical-equilibrium methods, Hibbard (1931) has found that the former method for obtaining soil extracts, although resembling the action of roots more than does the latter, does not show the ability of a soil to supply growing plants continuously with phosphorus so well as was hoped.

Relative-solubility method for soil phosphates, developed by Lemmermann (Ger., 1923-1926), has been proposed for obtaining more accurate knowledge of the availability of soil phosphorus. Essentially, this method consists in extracting soil materials with hot 10-percent hydrochloric acid and then with 1-percent citric acid. When the quantity of phosphorus extracted by the weak citric acid is less than 25 percent of that extracted by the stronger acid, the soil represented is likely to respond to phosphates. Investigators in different countries have reported varying results with this method.

Rapid colorimetric tests for determining the need for phosphate fertilizers have been developed, which simplifies the procedure and makes possible quick and accurate measurements of small quantities of phosphorus. Worthy of note are two very sensitive and rapid colorimetric tests developed by Bell and Doisy (1920) and Denigès (Fr., 1920). Practical applications of Denigès' method have been made by several soil investigators.

Several experiment stations have published useful information regarding practical methods for use in determining whether soils are deficient in available plant nutrient elements.

Water extractions. Water-extraction methods for determining the need for fertilizers have also been proposed, in which the primary object is to remove the water-soluble soil nutrients; and on the basis of results thus obtained, the need for fertilizers may

be determined. Von Wrangell and collaborators (Ger., 1926-1930) have developed a method for estimating available phosphorus which involves successive extractions. A common criticism of such methods is that root action is not taken into consideration.

Owing to the fact that nitrates are not affected to any appreciable degree by soil absorptive properties, fairly good results may be obtained, so far as soil nitrates are concerned, by soil-extraction methods. Morgan (1930) has suggested the use of diphenylamine for quick determination of soil nitrate. Obtaining suitable samples of soil material constitutes an important problem.

Soil-solution studies. Although soil-solution studies were not proposed for determining need for fertilizers, they may show in a general way the ability of fertile soils to maintain more concentrated soil solutions, as compared with soils of low producing power, thus indicating the importance of fertilizers on poor soils in increasing the quantity of available nutrients or the concentration of the soil solutions.

Soil reaction and need for phosphates. A relationship commonly exists between soil acidity and available soil phosphorus, as this element is commonly deficient in strongly acid soils. Strong soil acidity, therefore, may indicate the need for phosphates. Before applying superphosphate to strongly acid soils, it is usually desirable first to adjust soil reaction to about slight acidity through the use of agricultural lime (Ch. 17). (See under "Soil phosphorus" in Index.)

Pot tests. Growing plants in pots and adding fertilizer and other substances originated as a result of man's desire to know the cause of plant growth. Among the earliest records are to be found descriptions of pot tests conducted by Van Helmont in 1620 and by Woodward in 1669 (Ch. 1). The earliest modern scientific work pertaining to nutrition of plants was done by Home (1755-1757), when he was requested by the Edinburgh Society for the Improvement of Arts and Manufacture to try chemistry in determining principles of agriculture. He inaugurated pot experiments (1757), but made little progress with them.

In later years, pot tests were used for various purposes. Soil investigators, generally, make use of them because of their value in giving information about soils relative to their needs for fertilizers. Wagner (Ger., 1915-1920) has devoted much study to pot

tests, probably more than any other investigator. This method consists essentially in filling a number of pots with soil material,

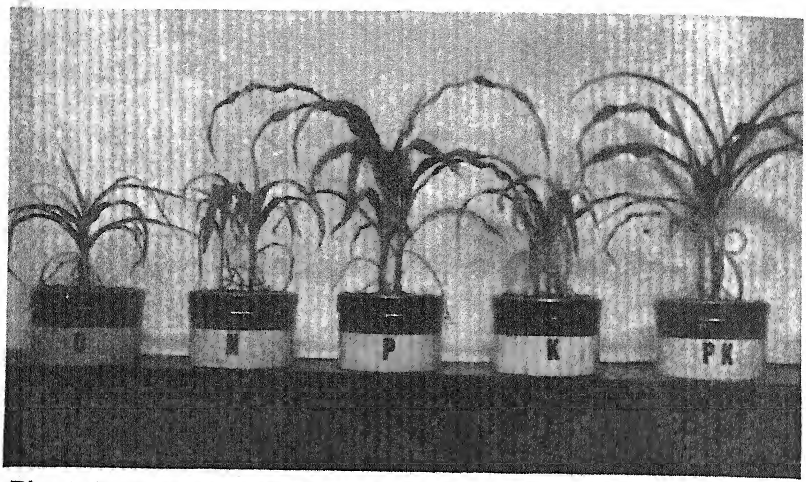

Fig. 125. A pot test showing the need for phosphate fertilizer: O, untreated; N, nitrogen fertilizer only; P, phosphate; K, potash; PK, phosphate and potash.

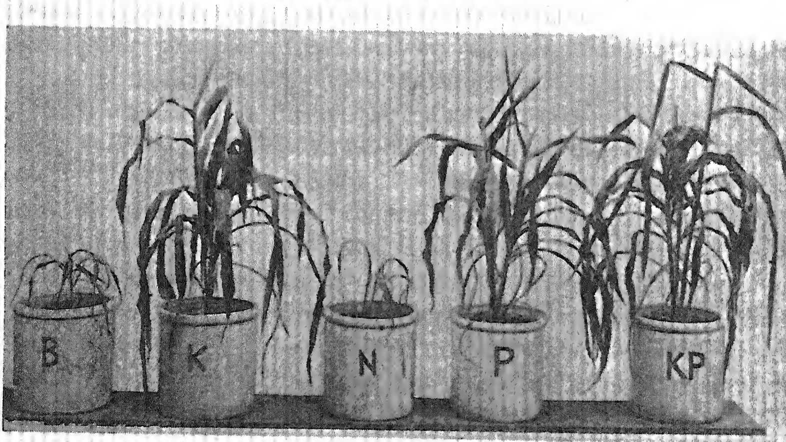

Fig. 126. A pot test in which corn on a marsh soil shows the need for both potash and phosphate fertilizers: B, untreated; K, potash; N, nitrogen; P, phosphate; KP, both potash and phosphate.

and adding fertilizing salts singly and in combinations. The crop used as an indicator is usually a cereal, and the need for fertilizer may be indicated by the growth, quantity of dry matter produced, and by ash analysis (Figs. 125 and 126).

Many variations in pot-testing work have been made by various investigators. When conducted with greenhouse and enclosure facilities, pot-testing affords an opportunity for controlling many of the uncontrollable factors commonly met in conducting field tests, including soil variations, moisture supply, temperature, birds and rodents, and insect pests. Generally, pot tests are regarded as ranking second to field tests for reliability (Fig. 127).

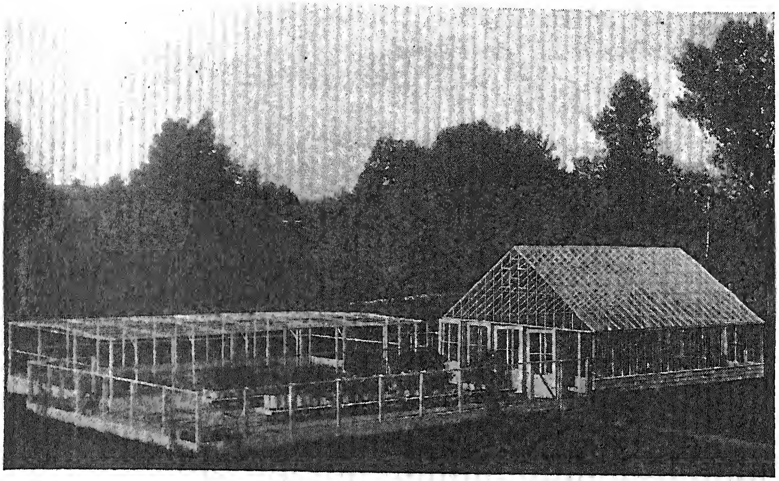

Fig. 127. Pot tests conducted with greenhouse and enclosure facilities. (R. I. Agr. Expt. Sta.)

Mitscherlich's method of pot-testing is based on a "law" relating to plant growth (see Index). Mitscherlich (Ger., 1909-1927) found that by growing oats in pots containing soil material and sand, and finding the weight of dry matter at maturity, the needs for phosphate and potash fertilizers could be assessed. Ten pots are required for testing a soil: 1 with undiluted soil material; 3 with a mixture of half soil material and half sand, treated with a complete fertilizer; 3 with a similar mixture, treated with fertilizer without phosphorus; and 3 with a like mixture, treated with fertilizer without potassium. Results obtained by other investigators by the use of this test have not agreed with those obtained by the author of the method. Mazé (Fr., 1912) has called attention to the importance of concentration and ratio of the constituents in the nutritive mediums. Lemmermann and co-workers (Ger.,

1928) have pointed out that, contrary to Mitscherlich's assumptions, the effect values of individual nutrients are not independent of other growth factors.

Cylinder and tank tests. Cylinders and tanks of varying sizes and kinds are also used for testing the fertilizer needs of crops on various soils, determining comparative efficiency of fertilizers and green manures, and for other purposes. Usually such tests are

Fig. 128. Cylinders used in determining proper soil-management practices. (N. J. Agr. Expt. Sta.)

conducted in the open, like field tests, and under similar conditions except for uniformity of soil materials (Fig. 128).

Neubauer-Schneider seedling method. A plant-culture method for determining needs for phosphate and potash fertilizers has been developed in Germany by Neubauer and Schneider (1923). A brief description of this method follows: A mixture of 100 grams of soil material and 50 grams of fine sand is placed in a glass dish. On top of this layer is placed 250 grams of fine sand, moistened with water. In this are planted 100 rye seeds that have been previously weighed and soaked in Uspulun, a disinfecting solution. The seedlings are allowed to grow for 17 days, after which they are dried, weighed, and the quantities of phosphorus or potassium taken up by the plants are determined.

On rather fertile soils, absorptions of less than 8 milligrams of P_2O_5 and 24 milligrams of K_2O indicate the need for phosphate and potash fertilizers, respectively. On less fertile soils, lower limits may be used. Under Indiana conditions, Thornton (1931) has suggested limit values of 4 milligrams for P_2O_5 and 10 for K_2O.

Many investigators have found a close relationship between exchangeable potassium and root-extracted potassium, hence some have concluded that there seems to be no advantage in the seedling method over base-exchange or dilute-acid methods. Conflicting results have been obtained with phosphorus. However, for many heavier-textured mineral soils, particularly, this method has given satisfactory results, as compared with pot and field tests, and has proved to be of practical value.

Plant symptoms indicate need for fertilizers. Agronomic literature contains considerable information regarding the effects that deficiencies of nutrient elements have on the growth and appearance of crop plants. On careful diagnosis, some of these symptoms may indicate rather definitely certain nutrient needs of plants or the need for fertilizers.

Nitrogen needs are commonly indicated by reduced intensity of green color of the leaves. Light-green color of the leaves of fruit trees, shade trees, cereals, lawn grasses, and of house plants are examples. Indian corn and small grains on flooded or water-soaked fields are also in this class. In tobacco, a deficiency of nitrogen is shown by a light-green color of the whole plant, with more or less yellowing and dying or "firing" of the lower leaves. "Yellowberry" of Turkey red wheat may indicate a nitrogen-deficiency problem in dry farming.

Phosphorus needs are not easily detected by plant symptoms, other than stunted growth. Sometimes the need for this element is indicated by premature ripening. With tobacco and sugar beets, a shortage of phosphorus produces plants that have an abnormally dark-green color, resulting from an accumulation of unused nitrate reserves. Kraybill and Smith (1924) found that tomato plants deficient in phosphorus were restricted in growth, became deep-green, and later they commonly showed a pronounced purple tinge.

Potassium needs of plants are more definitely indicated by deficiency symptoms than are phosphorus needs. Plants differ as to effects produced by potassium deficiency, as shown by the following examples.

Cotton. Deficiency of potassium causes a condition that is commonly called "cotton rust" (Skinner, 1926).

Grass. Slow growth, browning of tips of leaves, and leaves that die down without turning yellow, as may be commonly observed on potassium-deficient peat soils.

Indian corn. Development of marginal leaf "firing," and tendency of plants to die prematurely, particularly on sandy soils (Hoffer, 1927).

Potatoes. Retardation of growth, dark-green color of leaves, leaves with a wrinkled appearance, and developing of yellowish spots (which gradually turn brown) between the leaf veins, or appearance of bronzing effect on the leaves (Krueger and Wimmer [Ger.] and Brown).

Sugar beets. Leaves remain green, yellow spots appear between the veins and quickly turn brown, and whole leaf finally withers without intermediate yellowing (Krueger and Wimmer).

Spring wheat. Retardation of growth, tendency to lodge, and delayed ripening (Krueger and Wimmer).

Tobacco. Yellowing, or chlorosis, begins at the tip of the leaves and spreads over the surface, being followed commonly by the appearance of numerous small specks of dead tissue. Leaf growth is uneven, and the surface becomes rough and puckered (Garner, 1930).

Magnesium, manganese, and iron needs in plant nutrition are commonly indicated by chlorotic condition of the leaves (Figs. 31 and 32). Malnutrition may result from deficiencies of magnesium and manganese in soils. Chlorosis caused by a deficiency of available iron may be induced by an excess of calcium or manganese (see Index). According to Pettinger and co-workers (1932), chlorosis in maize caused by magnesium deficiency is characterized by continuous streaks with ragged edges, whereas chlorosis caused by manganese deficiency is characterized by discontinuous streaks that are distributed at random in the intervascular tissues.

In tobacco, magnesium deficiency is indicated by "sand-drown"; and calcium deficiency, by young leaves becoming diseased as they unfold from the buds and assume an abnormal shape.

Sap analysis. Analyzing plant sap to aid in determining the need for fertilizers originated with Gilbert and Hardin (1927) who found a close relation between the quantities of nitrogen, phosphorus, and potassium in expressed saps of several species of crop plants and in fertilizer treatments. They suggested certain limit values of concentration of the respective elements to indicate the need for fertilizers. McCool and associates (1928-1930) have shown that the use of fertilizer and the condition of the soil in regard to productivity markedly affect the composition of the saps, but they

drew no conclusion regarding the practical value of sap analyses. Pettinger (1931) in Virginia and Pierre and Pohlman (1933) in West Virginia have found that sap analyses give promise of having value in determining the need for fertilizers, and in studying soil and plant relationships.

Testing plant tissues. Testing split corn stalks (maize) chemically, to aid in determining needs for nitrogen and potash fertilizers, has been proposed by Hoffer (1926). The stalks are split lengthwise, and the test for nitrogen is made by applying a few drops of a diphenylamine solution to the freshly cut tissue between the joints. If no blue color develops, it is assumed that the soil concerned is deficient in available nitrogen. Potassium needs are determined by testing for accumulated iron compounds in the joint tissues by first applying a few drops of a 10-percent aqueous solution of potassium thiocyanate and then a drop or two of dilute hydrochloric acid. If in most stalks tested, intense reddish color results, the need for potash fertilizer is assumed. No general agreement has been reached by agronomists regarding the value of these tests, particularly for indicating the need for potash fertilizer. Other plant-tissue tests have been proposed.

Bacterial and fungous methods. Several bacterial methods for determining nutrient deficiencies of soils have been proposed. These methods are based on the assumption that certain relationships exist between bacterial activity and growth of crop plants. Descriptions of 2 such methods—one concerned with nitrogen and the other with phosphorus, potassium, and calcium—follow.

Nitrification largely determines the supply of available nitrogen in soils. The fact that the activity of nitrifying bacteria varies widely in different soils has given rise to the concept of ''nitrifying power'' of soils. Comparable results for a given series in a test are obtained by exposing soil materials to uniform conditions for a certain time. The nitrifying power is measured in terms of quantity of nitrate produced by a unit weight of soil material. Several investigators have found a more or less significant relation between nitrifying power of soils and crop growth. It is assumed that low nitrifying power indicates the need for nitrogen fertilizer.

Azotobacters used as indicators for available phosphorus in soils were proposed by Christensen (Den., 1914-1915). These organisms have also been used to indicate available potassium and calcium. The method used, as developed by Winogradsky (1925-1928), con-

sists, essentially, in stimulating the growth of these free-living, nitrogen-fixing bacteria, which are very sensitive to deficiencies of these mineral nutrients, by adding different plant nutrients to a weighed quantity of soil material. This soil material is moistened and molded into plaques on the smooth surface of which grow colonies of azotobacters. Deficiencies of the respective mineral elements are indicated by the most luxuriant growth of azotobacters, in response to the fertilizing element needed. This method is commonly used in parts of Europe. Green (1932) and Pittman and Burnham (1932) have concluded that, in Arizona and Utah, the plaque method is limited principally to soils that are extremely deficient in phosphorus. Others have found this method satisfactory for determining the need for potash fertilizers.

Aspergillus niger, a group of widely distributed soil-inhabiting fungi (mold) that are very sensitive to deficiency of phosphorus, may be used instead of azotobacters as an indicator of available soil phosphorus, potassium, and magnesium. Various investigators have found this method simple and reliable, and claim that it may be used in a practical way for determining the need for phosphate and potash fertilizers.

FIELD TESTS AND SOIL EXAMINATIONS

The most reliable information regarding need for fertilizers may be obtained by means of properly conducted field tests. Such tests are usually made by measuring off a series of plots and treating them in different ways with fertilizers and, if necessary, with lime. Increase in growth and yield of the crops grown indicates the need for fertilizer and lime.

The reliability of field tests is established by the fact that they are conducted under field conditions and on soils in their natural positions. These advantages were early appreciated by Boussingault who introduced the method of exact field experiments in 1834 (see Index). Lawes carried his fertilizer tests to the field, and so did Liebig and Ville. Field experiments have become the standard method of agricultural experiment stations (Fig. 129).

Old v. new. In much of the early field-test work, the interest lay in determining the fertilizing value of nutrient-containing salts, in showing that crop yields could be increased by "artificial manures," in comparing chemical fertilizers and barnyard manures, and in establishing certain principles of fertilizer practice. Inas-

much as the results of these earlier field experiments have become embodied in general farming experience, modern long-time field tests are concerned more with other problems, such as comparison of similar fertilizers, effects of fertilizers on crops, efficiency of fertilizer practices, economic use of fertilizers in crop rotation, etc., which involve more careful procedure and interpretation.

Fig. 129. The Jordan Soil-Fertility Plots of Pennsylvania Agricultural Experiment Station are among the oldest in the United Sates. (Pa. Agr. Expt. Sta.)

Conducting field experiments. Much can be said regarding the manner in which field experiments are conducted; but as space will not allow a lengthy discussion, attention will be directed to only a few points.

The plan of an experiment is determined by its purpose. Much depends on uniformity of soil, soil drainage, air drainage, and previous soil treatment. Open fields are advisable, and proximity to wooded areas, orchards, and large buildings should be avoided. Long, narrow plots are usually laid out in series with an adequate number of check plots. Commonly, two treated plots are located between two check plots—that is, every third plot is a check plot. The yields from the check plots may serve as a means for evaluating the effects of the various treatments by direct comparison, or

by the grading or progressive method in which it is assumed that any variation in soil between two successive check plots is uniformly graded or progressive. To illustrate:

Given a series of plots in a fertilizer test on wheat, every third plot being a check. The average yields for the plots are given in terms of bushels per acre:

15	30	29	16.5	28	32	17	35	30	16
C_a	T_1	T_2	C_b	T_3	T_4	C_c	T_5	T_6	C_d

To obtain the correct increase on plot T_1, for example, a variation due to soil heterogeneity must be taken into account. It is assumed that the variation from C_a to C_b is progressive, or uniformly graded. Hence the increases in yields on plots T_1 and T_2 may be determined by interpolation, as follows:

$$T_1 - (C_a + \frac{C_b - C_a}{3}) = 14.5 \text{ bushels}$$

$$T_2 - (C_a + \frac{C_b - C_a}{3} \times 2) = 13.0 \text{ bushels}$$

Plots in field tests that are designed for rotation and fertilizer studies should be laid out in different series to allow the growing of each crop every year. The work required to conduct field tests that involve comparisons of several rotations and fertilizer treatments is enormous.

Results of permanent field experiments may have rather wide or very limited application, depending on the nature of the experiments and the kinds of soils on which they are located. They have the greatest value when conducted on predominating types of soils, and when dominant soil characteristics are taken into consideration when the experiments are planned. The aim should be to search for principles on which to base sound fertilizer and soil-management practices. Short-time field experiments are especially subject to errors, particularly when a short period does not include a cycle of seasonal fluctuations.

Much depends on correct interpretation of results and on determining whether certain results are significant. Some of these problems are discussed in the following chapter.

Triangle system of fertilizer experiments. Field experiments have been modified in many ways. One of the modified forms is

the so-called "triangle system" which has been proposed by Schreiner and Skinner (1918) and is based on their work with culture solutions. The name of this scheme was suggested by the fact that the fertilizer treatments may be indicated on a triangle. In Figure 130 are indicated 21 fertilizer treatments in 20-percent stages, as follows:

The points of the triangle represent applications of single-element fertilizers—20(N)-0-0; 0-20-0; and 0-0-20. The sides of the triangle represent 12 mixtures with two fertilizing constituents, including 4(N)-16-0; 8-12-0; 4-0-16; 8-0-12; 0-4-16; 0-8-12; etc. The intersections within the triangle represent 6 complete mixtures, as follows: 4(N)-12-4; 4-8-8; 4-4-12; 8-8-4; 8-4-8; and 12-4-4.

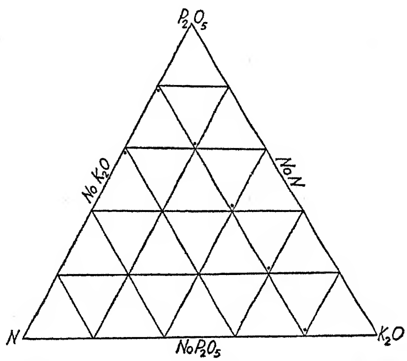

Fig. 130. A triangle indicating 21 fertilizer combinations in 20-percent stages. The points of the triangle represent single-element fertilizers, such as 20(N)-0-0, 0-20-0, and 0-0-20. The sides represent 12 mixtures with two fertilizer constituents, such as 4-16-0, 8-12-0, 4-0-16, etc. The intersections within the triangle represent 6 complete mixtures, including 4-12-4, 4-8-8, 4-4-12, etc.

It is to be noted that when the percentage of one constituent is increased or decreased, the percentage of one of the other two is decreased or increased accordingly, in order to maintain the same number of units.

A common objection to this scheme is the fact that the results do not lend themselves to statistical treatment. Furthermore, if good results are obtained with a 4(N)-8-8 mixture, there is no way to determine what the response would be from a mixture having additional nitrogen but with the same percentages of P_2O_5 and K_2O, for more nitrogen might make a better fertilizer.

Farm fertilizer tests. Permanent fertilizer experiments made on a particular soil may prove to be of little or no value in solving soil-fertility problems on different kinds of soils on which fertilizers are needed. However, simple fertilizer and lime tests can be conducted easily on individual farms and, if necessary, in different fields. Many farmers have conducted such tests.

A strip through a field may be treated; or two or more plots

Fig. 131. A strip through an oat field, fertilized with phosphate. Left—Unfertilized grain gave a yield of 69.5 bushels per acre. Right—Oats fertilized with 300 pounds of superphosphate (16-percent) per acre gave a yield of 87 bushels.

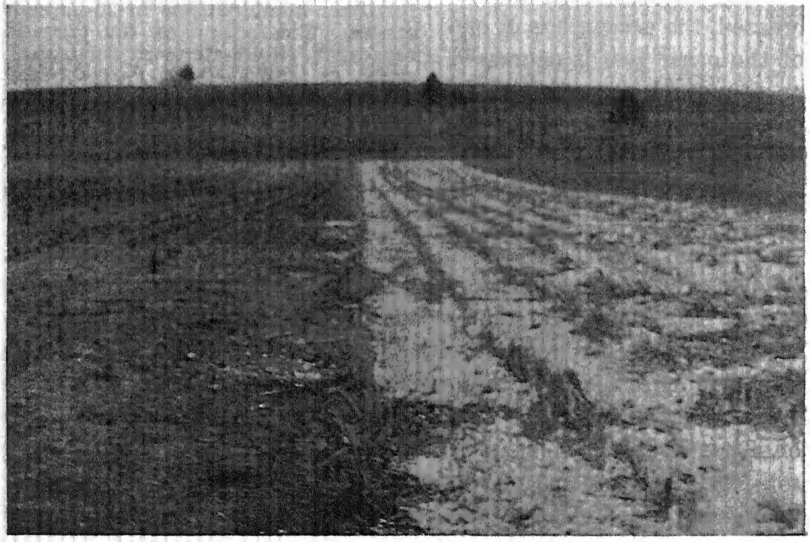

Fig. 132. A limed strip through a field of acid soil.

may be laid out, projecting into the field, and fertilized differently, with and without lime. A few rows may be fertilized; likewise square-rod areas in fields and on grassed areas (Figs. 131 and 132). Conversely, if there is any doubt as to the value of a particular fertilizer that is being used, a strip of one row or a few rows may be left unfertilized (Fig. 133).

Fig. 133. A row of corn left unfertilized.

Soil examinations. In solving specific soil-fertility problems and in determining the need for fertilizer, it is usually advisable to examine first the soil or soils concerned under field conditions, if possible. In such examinations, the following factors should be considered: drainage; water supply; organic matter; nature of the subsoil; physical condition of the topsoil; inoculation (when legumes are involved); harmful agents (diseases and insect pests); cropping system; previous crop; and soil treatment.

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REVIEW QUESTIONS

1. How may one judge the fruitfulness of lands by the native vegetation? Give examples. What are the limitations of such a diagnosis?
2. Why did the early agricultural chemists devote so much time to analyzing plants for ash? What did such work lead to?
3. Discuss the theory regarding total soil analysis in relation to soil fertility.
4. On what basis did Dyer develop his citric acid method for measuring the availability of soil nutrient elements?
5. What prompted the development of the strong-acid digestion methods for determining the ability of soils to grow crops?
6. What are the principal points of weakness of the percolation and water-extraction methods for determining the lack of plant-food elements in soils?
7. Explain the relationship between available soil phosphorus and soil reaction.
8. Compare the use of pots, cylinders, and field plots for determining the deficiency of available plant nutrients in soils.
9. Describe some of the plant symptoms that indicate the need for fertilizers.
10. Describe some of the practical tests for diagnosing the ability of soils to grow crops.
11. How may farmers find out whether they should use lime or special fertilizer?

CHAPTER 27

INTERPRETING RESULTS OF FERTILIZER EXPERIMENTS

When one examines the results of a series of modern fertilizer experiments, he finds that the yields from the different plots may vary considerably, as the result of annual variation in weather, soil deterioration or improvement, and other causes. Included in these variations are certain "errors" that cannot be ascribed to carelessness in measuring the plots or in weighing the produce. Such errors are usually regarded as the result of soil inequality or heterogeneity. Much has been done to eliminate these errors or to reduce them to the minimum by better arrangement of the plots and by keeping comparative plots close together or adjacent if possible.

RELIABILITY AND SIGNIFICANCE OF RESULTS

In modern field experiments, it is important to know the character of the soils, whether results are reliable, and whether certain results have any significance when compared with others. For example, plots A and B of a series have produced average yields of 62.05 and 55.95 bushels of Indian corn to the acre, respectively. What confidence can one place in these results? Does the average yield on plot A establish the fact that the fertilizer treatment given that plot is better than that given plot B? After a consideration of questions regarding such factors as seed, planting, and care of the crop, among other questions that may arise regarding plots A and B are: Is the soil of the former plot like that of the latter? and Is the soil of these plots typical of the area covered by the experiment? These questions represent important problems in interpreting results of fertilizer experiments.

Probable error. Seldom, if ever, is the soil of a given area so uniform that every plot of an experiment will represent the same soil conditions. Because of soil inequality, the yields from a number of similarly treated plots may vary more or less, say between

extremes of 30 and 40 bushels of wheat to the acre, with an average, or mean, of 35 bushels. But 35 bushels an acre is not the experimental truth regarding the yielding power of the plots considered. The fact is that the plots produced an average yield of 35 bushels and the yields varied, in the extremes, 5 bushels both ways from the mean. The truth regarding the yields of the plots considered, as nearly as can be determined, is that the yields of half of the similarly treated plots fall within a range of about 1.6 bushels below and above the mean, or between about 33.4 and 36.6 bushels, as shown later.

In a great many experiments, the questions of reliability and significance finally turn on the value of an average, or mean, of a set of observations, on significance of difference between trends (Fisher), or on the mean of the difference between two sets of paired results, as in "Student's method," discussed later.

In scientific work, the experimental truth regarding the yield of wheat on the similarly treated plots referred to, for example, may be expressed by the average yield plus the concept of *probable error,* commonly called "probable error of the mean."

Basis of probable error. Probable error is based on the theory of probability, or the "law" of chance, which may be illustrated as follows: What are the chances of getting all heads up in tossing three coins? Out of 100 trials, one may obtain these results: all heads turned up, 8 times; 2 heads up, 40 times; 2 tails up, 42 times; and all tails up, 10 times. A frequency-distribution curve representing these results is bell-shaped (Fig. 134).

Probable error and significance of results. Probable error expresses the quartile deviation from the mean of a given set of measurements, indicating that another measurement is just as likely to fall outside the range of probable error as within it. Probable error is always associated with the mean of a set of observations or results. Just one observation is not absolutely right; the mean or average of a number of observations comes nearer the experimental truth, with a 50–50 certainty that other yields will fall within a range of deviation from the mean, as indicated by the probable error. *Probable error is not a property of any single observation or result, but rather it is a property of a set of observations.*

Expressing probable error. The earliest use of the probable-error concept was made by Bessel, a Prussian astronomer, in 1815.

The conventional way of expressing this "error" is as follows: $X = 5.6 \pm 0.3$, which means that the quantity "X" has an average value of 5.6 with a "probable error" (P.E.) of ± 0.3. The "error" of ± 0.3 means that another measure of the value of "X" is as likely to fall within the limits of 5.3 and 5.9 as to fall outside these limits. The chances are 50–50, or 1 to 1, that another observation will fall within these limits.

In statistical studies, therefore, probable error is not an error or mistake at all, but is rather a deviation below and above the most

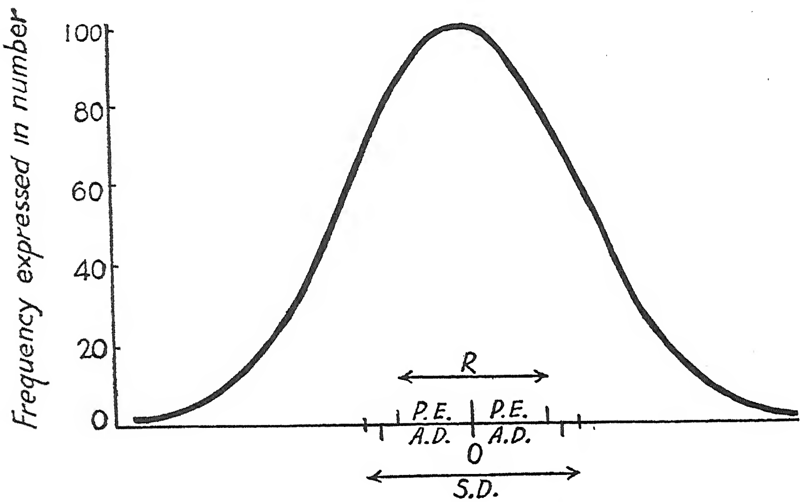

Fig. 134. A normal frequency curve, illustrating the theory of probability: O, average or mean; A.D., average deviation from the mean; P.E., probable error, or quartile deviation from the mean; S.D., range of standard deviation; R, probable-error range.

probable value (average, or mean), and a deviation which indicates a range within which half the results of a number of observations or similarly treated plots can be expected to fall. Hence it may be called the "probable deviation."

Probable error illustrated. Figure 134, a normal frequency curve, might indicate the yields of wheat obtained on 100 similarly treated plots of an experiment. An average, or mean, say of 35 bushels, is represented by 0 on the abscissa. This is the most probable yield. Probable error of this mean is represented on the abscissa by "P.E.," which is the quartile deviation below and above the mean. This defines the range within which half the

yields are likely to fall, and indicates that the chances are 1 to 1 that other yields will fall within this range.

Because of relationships, a clearer understanding of probable error, or quartile deviation, of a mean calls for a knowledge of *average deviation* (A.D.) and *standard deviation* (σ).

Average and standard deviations. The meanings of average and standard deviations and their differences may be illustrated as follows:

Average Deviation (A.D.)		Standard Deviation (σ)		
Wheat Yield on 5 Similarly Treated Plots	Deviation from Mean (D)	Wheat Yield from Same 5 Plots	Deviation from Mean (D)	Deviation from Mean, Squared (D^2)
Bushels		*Bushels*		
36	1	36	1	1
33	2	33	−2	4
35	0	35	0	0
37	2	37	2	4
34	1	34	−1	1
5|175	5|6	5|175		5|10
Mean = 35 bu.	A.D. = 1.2 bu.	Mean = 35 bu.		2
		Standard deviation (σ) = $\sqrt{2.00}$ = 1.414 bu.		

Average deviation is the arithmetic mean of the deviations from the arithmetic mean of the data, and is derived according to the formula,

$$\text{A.D.} = \frac{\Sigma D}{n}.$$

Standard deviation is the square root of the arithmetic mean of the squares of the deviations of the various items from the arithmetic mean of the data, and is derived according to the formula,

$$\sigma = \sqrt{\frac{\Sigma D^2}{n}}.$$

The range of deviation in A.D. is less than it is in S.D. (See Fig. 134.)

Determining probable error. Probable error is usually determined according to the following formula:

$$\text{P.E.} = \sigma \times 0.6745 = \sqrt{\frac{\Sigma D^2}{n}} \times 0.6745$$

This is interpreted as:

$$\text{Probable error} = \sqrt{\frac{\text{Sum of the squares of deviations from mean}}{\text{number of observations}}} \times 0.6745$$

Application of the probable error concept is made to results obtained on 10 similarly treated plots, as follows:

Yield of Wheat per Acre		Deviation from Mean	Deviation Squared
Plots	*Bushels*	(D)	(D^2)
1	36	1	1
2	33	—2	4
3	35	0	0
4	36	1	1
5	34	—1	1
6	38	3	9
7	33	—2	4
8	35	0	0
9	31	—4	16
10	39	4	16
	10 | 350		$\Sigma = 52$
	Mean = 35		

$$\sigma = \sqrt{\frac{\Sigma D^2}{n}} = \sqrt{\frac{52}{10}} = 2.28$$

$$\text{P.E.} = \sigma \times 0.6745 = 1.54$$

Thus the results obtained on the ten plots may be expressed as 35 ± 1.54.

Probable error may also be used to determine significance of any particular result in a series of fertilizer tests, as compared with another. For example, two fertilizers are compared on two series of plots, series A and series B. The average yields of Indian corn obtained are 62.05 ± 2.2 and 55.95 ± 1.5 bushels, respectively. It would seem that the average yield for the A plots is distinctly significant. According to one method, it would be significant if three times the probable error of the difference of these two means is less than the difference of the means. This calculation is made in the following manner:

$$\begin{array}{rl} \text{A.} & 62.05 \pm 2.2 \\ \text{B.} & 55.95 \pm 1.5 \\ \hline & 6.10 \pm \sqrt{2.2^2 + 1.5^2} = \pm 2.66 \\ & \qquad\qquad\qquad\qquad 3 \\ \hline & \qquad\qquad\qquad\qquad 7.98 \end{array}$$

Inasmuch as 7.98 is greater than the difference of the means (6.10), there is no significance; that is to say, the average yield of 62.05 bushels has no significance, as compared with the average yield of 55.95 bushels. Such an application and interpretation will hold only when there are 30 or more observations involved, and when the grouping of the observations will represent a normal frequency–distribution curve.

Standard deviation, or standard error. Standard deviation (σ) has come into use as a measurement of the consistency of a set of observations or results. It is called the "mean-square error," and "standard error." It was introduced as the "mean error" by Gauss (Ger.) in 1821. This, as has been shown, is the square root of the mean of the squares of all the deviations from the mean. The value thus obtained lies beyond the limit points of probable error and average deviation on the abscissa of a normal frequency curve (Fig. 134).

Commonly, three times the standard error is regarded as the greatest degree to which a given observation is likely to be wrong. There are modifications of methods for obtaining probable and standard errors.

These are but the simple concepts of the measures of dispersion in statistics. According to Davies, probable error is applied when items are dispersed equally on each side of a point, the median. Average deviation is usually applied to economic data, and standard deviation is commonly used in correlation.

Importance of replication. When uncontrollable factors cause fluctuations in results, a considerable number of observations must be made in order to determine the true mean with any degree of accuracy. To measure adequately the variation in results due to soil heterogeneity, for example, a rather large number of plots receiving the same treatment are needed, distributed over the entire area covered by the experiment. This is necessary in order that all sources of variability that affect the experiment as a whole may enter into the different observations or results on which probable error and standard deviation are based.

Arrangement of field experiments. For the purpose of those simpler fertilizer experiments in which every possible comparison is of equal importance, Fisher (Eng., 1926) has proposed a "Latin-square" method of plot arrangement, after the Latin-square concept of Euler (1707-1783), a Swiss mathematician, as follows:

A B C D E		A B C D E
E A B C D		D E A B C
D E A B C	or	B C D E A
C D E A B		E A B C D
B C D E A		C D E A B

Many modifications of this arrangement of field plots may be made, depending on the purpose of the experiments and on field conditions.

Checkerboard method is another scheme proposed for laying out experimental plots in order to make possible a measurement of reliability of the results. Such a layout may be indicated as follows:

C T C T C		
T C T C T		A B A B A B A B A B
C T C T C	or	B A B A B A B A B A
T C T C T		A B A B A B A B A B
C T C T C		

The first illustration shows check plots (C) alternating with similarly treated plots (T), each treated plot being adjacent to either 3 or 4 check plots. The second illustration shows a layout in which two different fertilizer treatments are compared, the check plots being eliminated.

In general, only a comparatively few experiments include comparisons all of which are of equal importance. In most fertilizer experiments, the comparisons involve single factors, such as with and without a nutrient element, increased increments, etc. Furthermore, much land and labor are required to replicate all treatments adequately to provide sufficient data on which to base probable error or standard deviation. Most fertilizer experiments have not been laid out to allow application of the probable-error concept. In an orchard, suitable data may be obtained by selecting individual trees throughout the orchard. For small samples, test significance by Fisher's method, based on Student's method.

"Student's method." In most fertilizer experiments, the number of similarly treated plots is usually so small that it is impossible to apply the probable-error concept, or to determine the distribution of the observations or results in accordance with a normal frequency curve, as illustrated in Figure 134. In such experiments, as Love (1923) has pointed out, the principal interest lies in the comparison of yields obtained from any two treatments and not in the absolute yields of either one. It is of interest to know

both the average gain of one over the other, for a period of years, and also the consistency of that gain. Thus the problem involves a comparison of the results obtained for each year in the order in which they were obtained.

Gosset, an English statistician (1908), writing under the pen-name of "Student," has proposed a method, called "Student's method," for dealing with the problem of the interpretation of results of experiments. In this method, parallelism of paired observations is taken into consideration, and weight is given to the quantity and consistency of the differences in estimating the significance of the mean difference. An application of Student's method is made to paired results obtained on Indian corn grown on plots 17 and 26 in a 5-year rotation at Wooster, Ohio, as shown in the following table:

STUDENT'S METHOD ILLUSTRATED

Year When Results Were Obtained	Paired Results, Yields per Acre		Difference in Yields Plot 17 over Plot 26	Deviation of Differences from Mean Difference (0.78)	Deviations Squared (D^2)
	Plot No. 17 *	Plot No. 26 †			
	Bu.	*Bu.*	*Bu.*		
1894	20.50	18.32	2.18	1.40	1.96
1895	—	—	—	—	—
1896	56.89	59.43	−2.54	3.32	11.02
1897	31.79	42.96	−11.07	11.85	140.42
1898	33.93	38.75	−4.82	5.60	31.36
1899	40.50	34.50	6.00	5.22	27.25
1900	48.68	41.32	7.36	6.58	43.30
1901	60.64	63.14	−2.50	3.28	10.76
1902	75.57	89.18	−13.61	14.39	207.07
1903	22.32	23.43	−1.11	1.89	3.57
1904	40.04	36.46	5.58	4.80	23.04
1905	58.64	49.18	9.46	8.68	75.34
1906	63.32	64.54	−1.22	2.00	4.00
1907	48.29	64.57	−16.28	17.06	291.04
1908	44.96	43.64	1.32	.54	.29
1909	45.07	33.67	11.40	10.62	112.78
1910	17.07	12.03	5.04	4.26	18.15
1911	71.75	69.10	2.65	1.87	3.50
1912	—	—	—	—	—
1913	42.50	26.25	16.25	15.47	239.32
Mean	45.70	44.90	+0.78		69.12
					$\sigma = 8.31$

* Fertilizer treatment consists of 60 pounds of nitrate of soda, 25 pounds of dried blood, 160 pounds of superphosphate, 100 pounds of muriate of potash, applied to wheat; and 80 pounds of nitrate of soda, 160 pounds of superphosphate, and 80 pounds of muriate of potash, applied to corn and oats.

† Fertilizer treatment consists of 50 pounds of dried blood on wheat; 120 pounds, 240 pounds, and 240 pounds of nitrate of soda, applied on wheat, corn, and oats, respectively; bone meal equivalent to 160 pounds, 80 pounds, and 80 pounds of superphosphate, applied to wheat, corn, and oats, respectively; and 100 pounds, 80 pounds, and 80 pounds of muriate of potash, applied to wheat, corn, and oats, respectively.

Mean of difference (0.78) $\div$ 8.31 (σ) $= 0.0939 =$ Z of Student, indicating probability (P) which may be expressed as ± 0.6575, for 18 observations.

Probability of $0.6575 =$ odds less than 2 to 1. But odds of 30 to 1 indicate significance. Accordingly, the mean of the difference (0.78) with probability of ± 0.6575 indicates that no significance is to be attached to the average yield obtained on plot 17, as compared with that obtained on plot 26.

Corresponding values of Z may be found in "Student's" original article in *Biometrika* 11:414-417, 1917, and in Pearson's *Tables for Statisticians and Biometricians.*

Odds are obtained as follows:

$$\text{Odds} = \frac{\text{Probability value for Z (0.6575)}}{\text{1.0000 minus probability value for Z}}$$

Odds v. probable and standard errors. The concept of odds is another way of expressing chance or probability. Probable error of a set of observations indicates even chances, or odds of 1 to 1, that another observation would fall within the limits prescribed. Standard deviation (σ) of a set of observations indicates odds of 2 to 1, or that there are 2 chances for another observation to fall within the range indicated, against 1 chance that it would fall outside those limits.

Paired yields v. paired increases. Results obtained by the use of Student's method have value only when the paired observations are comparable. In fertilizer experiments, paired *yields* are usually used to obtain the mean difference from which are derived the deviations on which significance is based. But parallelism of yields may not give reliable results, because soil heterogeneity may prove to be a disturbing factor. To illustrate: Paralleling the *yields* of Indian corn obtained on plots A and B may show odds of 195 to 1 in favor of treatment A, whereas the mean of the *increases* actually obtained may be exactly the same, or the mean increase of B may be even greater than that of A. Common sense should tell at once that odds of 195 to 1, as based on paired yields, cannot be true.

When soil heterogeneity becomes a disturbing factor, it is desirable to apply Student's method to paired *gains* or *increases.* The following table will show the importance of this procedure:

Paired Yields v. Paired Increases in Student's Method

(Results with Indian Corn on Plots 17 and 26, Wooster, Ohio.)

Year When Observations Were Made	Paired Yields		Difference Between Yields, Plot 17 Minus Plot 26	Deviation of Difference from 0.78, the Mean of Difference	Deviation Squared D^2	Paired Increases		Difference Between Increases, Plot 17 Minus Plot 26	Deviation of Difference from 4.31, the Mean of Differences	Deviation Squared D^2
	Plot 17	Plot 26				Plot 17	Plot 26			
	Bu.	*Bu.*	*Bu.*			*Bu.*	*Bu.*	*Bu.*		
1894	20.50	18.32	2.18	1.40	1.96	−0.62	1.80	−2.42	6.73	45.29
1895	——	——	——	——	——	——	——	——	——	——
1896	56.89	59.43	−2.54	3.32	11.02	5.80	8.74	−2.94	7.25	52.56
1897	31.79	42.86	−11.07	11.85	140.42	13.11	9.48	3.63	.68	.46
1898	33.93	38.75	−4.82	5.60	31.36	8.06	7.24	.82	3.49	12.18
1899	40.50	34.50	6.00	5.22	27.25	18.81	10.36	8.45	4.14	17.14
1900	48.68	41.32	7.36	6.58	43.30	21.35	10.75	10.60	6.29	39.56
1901	60.64	63.14	−2.50	3.28	10.76	19.35	28.64	−9.29	13.60	184.96
1902	75.57	89.18	−13.61	14.39	207.07	23.25	22.92	.33	3.98	15.84
1903	22.32	23.43	−1.11	1.89	3.57	19.67	13.83	5.84	1.53	2.34
1904	40.04	34.46	5.58	4.80	23.04	22.95	19.40	3.55	.76	.57
1905	58.64	49.18	9.46	8.68	75.34	20.86	18.25	2.61	1.70	2.89
1906	63.32	64.54	−1.22	2.00	4.00	28.12	29.33	−1.21	5.52	30.47
1907	48.29	64.57	−16.28	17.06	291.04	12.98	17.56	−4.58	8.89	79.03
1908	44.96	43.64	1.32	.54	.29	20.16	10.51	9.65	5.34	28.52
1909	45.07	33.67	11.40	10.62	112.78	25.29	14.11	11.18	6.87	47.20
1910	17.07	12.03	5.04	4.26	18.15	13.09	3.19	9.90	5.59	31.25
1911	71.75	69.10	2.65	1.87	3.50	35.28	25.02	10.26	5.95	35.40
1912	——	——	——	——	——	——	——	——	——	——
1913	42.50	26.25	16.25	15.47	239.32	29.87	8.58	21.29	16.98	288.32
Mean	45.70	44.90	+0.78	——	69.12 $\sigma=8.31$	18.74	14.43	+4.31	——	M=50.78 $\sigma=7.12$

$Z=0.0939$.
P = less than ±0.6575.
Odds = less than 2 to 1.

$Z=0.61$.
P = ±0.9886.
Odds = 87 to 1.

It is to be observed that when *yields* are paralleled, odds indicate that the fertilizer treatment given to plot 26 is as effective for corn as the treatment given plot 17; but that when *increases* are paired, the odds indicate that the treatment given plot 17 is the more effective for corn. Here the truth lies in the consistency in the *differences between the increases* obtained on the two plots.

Other illustrations may be given to show how a conclusion reached by applying Student's method to paired yields may be reversed when the method is applied to the corresponding paired increases.[1] In such cases the method should be applied to paired increases.

Statistical methods are aids only. Sometimes, in the interpretation of experimental results, statistical methods are favored even against common sense. Statistical methods are always intended as aids only. In a particular experiment, reliability and significance of certain results may be indicated and expressed in mathematical form through the use of statistical formulas, but it does not mean that the reliability and significance would hold were the experiment conducted on the same type of soil in another field or on another farm or a slightly different soil.

The significance of many results, therefore, as compared with certain others, may be plainly shown by simply plotting the annual average yields or increases of a number of similarly treated plots, together with comparable yields or increases, or by plotting paired observations. When, in such plotting, comparable results show, graphically, parallel arrangement at different levels, one needs no statistical formulas to determine the significance of the higher values. In the first half of the seventeenth century, Descartes, a famous French philosopher and mathematician, went so far as to formulate a principle to the effect that all things are true that we can see very clearly and distinctly. This reasoning would apply to the above parallel lines. But when the parallelism is broken at different points, thus showing in graphic form a more or less crisscross effect, then we must use some suitable statistical method to determine whether there is any significance in our different results, and whether this significance can be expressed mathematically. Statistical or biometrical methods must be used with great care, and experimental data must be interpreted with common sense, if conclusions reached are to be of any value. An important factor is selection of suitable data.

[1] WEIR, W. W. LIMITATION OF STUDENT'S METHOD WHEN APPLIED TO FERTILIZER EXPERIMENTS. Jour. Agr. Res. (U.S.), Vol. 31, No. 10. 1925.

CORRELATION

A word may be said regarding *correlation,* a statistical term commonly met with in discussions of soil-fertility problems. Correlation is relationship between two sets of data. For example, one set of data, including a large number of observations, may pertain to degrees of soil acidity; while another set, including an equal number of observations, may pertain to yields of barley on the same acid soils. If there is an agreement between pH values and yields—such as the fact that yields decrease as acidity increases—the relationship or correlation is called positive; and if there is no agreement, the correlation is negative.

Correlation implies fundamental relationships; that is, either one of two phenomena acts or reacts upon the other, or both may be affected by one or more common causes.

Coefficient of correlation. The measurement of correlation is expressed as *coefficient of correlation* which, in comparison of sets of paired values, expresses regression towards the values for the mean of all members of the sets. A high positive correlation may be expressed as +0.95, or +95.

The symbol of coefficient of correlation is "r," which represents a so-called "straight-line function," or a "linear relationship" between two sets of variables. An illustration of correlation, coefficient of correlation, and of two methods of computing "r" follows, in which the variables in the X series constitute the basis of comparison:

Correlation of X and Z Sets of Variables

X	Z	X·Z	X^2	Z^2
1	2	2	1	4
2	4	8	4	16
3	6	18	9	36
4	8	32	16	64
5	10	50	25	100
6	12	72	36	144
7	14	98	49	196
28	56	280	140	560

σ of X $(\sigma_X) = 2$ σ of Z $(\sigma_Z) = 4$

$$r = \frac{\dfrac{\dfrac{\Sigma X}{\sigma_X} \times \dfrac{\Sigma Z}{\sigma_Z}}{N}}{\dfrac{\left(\dfrac{\Sigma X}{\sigma_X}\right)^2}{N}} = \frac{\dfrac{\dfrac{28}{2} \times \dfrac{56}{4}}{7}}{\dfrac{\left(\dfrac{28}{2}\right)^2}{7}} = \frac{28}{28} = 1, \text{ or } 100$$

Mean = 4 8 40 20 80

Mean² = 16 64

$M_X \cdot M_Z$ = 32 $\quad \dfrac{-32}{8} \quad \dfrac{-16}{4} \quad \dfrac{-64}{16}$

$$r = \frac{8}{\sqrt{4 \times 16}} = \frac{8}{8} = 1, \text{ or } 100$$

The illustration represents a positive correlation of 100, as one may see by comparing the variables of the Z series with those of the X series.

The graphic method. Straight-line relationship, or correlation, between two sets of data may be shown graphically by taking the variables used as the base in the comparison for the ordinate and the other set of variables as the abscissa. By placing the number of observations for each variable of the set used as the abscissa in their respective places, the linear relationship will be indicated by the character of the distribution, as shown in the graphical table on p. 568.

Methods of correlation. Methods of correlation have been devised for dealing with relationships between two attributes or sets of variables and also with relationships in which there are three or more correlated attributes. Correlation of two attributes is called "normal correlation"; and of three or more, "multiple correlation." There may also be *partial correlation,* that is, correlation between two sets of variables when the remaining variables are taken to have fixed values.

EVALUATING FERTILIZERS ON THE BASIS OF EXPERIMENTAL RESULTS

Many experiments have been designed for the purpose of evaluating different fertilizers, particularly nitrogen fertilizers. In most of these experiments, equal quantities of phosphorus or of nitrogen are applied to the acre. Comparable results are usually expressed as increases per acre. When different nitrogen fertilizers are compared, for example, relative rating, based on effectiveness, is usually determined by dividing the acre increase obtained from one by that obtained from the base-relative fertilizer (usually nitrate of soda). This gives relative values of 100 (for nitrate of soda, or the base-relative fertilizer), 95, 88, etc. In comparing any two fertilizers, the relative rating is commonly determined by dividing the increase in yield of one by that of the other. For example, fertilizer A, with an average increase of 8 bushels of maize to the acre, may be regarded as being 80 percent as effective as fertilizer B, with an average increase of 10 bushels.

Similar fertilizers are also commonly compared on the basis of money value per ton, as determined by absolute or relative results obtained in field experiments.

Correlation of Yield of Grain Plus Straw from Entire Plot and Yield of Grain from 5 Rod Rows [2]

Grain + Straw from Entire Plot (Pounds)	Yield of Grain per Acre from 5 Rod Rows (Bushels)																Number of Observations of Yields from Rod Rows
	7.5	9	10.5	12	13.5	15	16.5	18	19.5	21	22.5	24	25.5	27	28.5	30	
22.5		1															1
27.5	2	2	2	1													7
32.5		2	7	2			1										12
37.5		1	10	12	4	3											30
42.5		1	3	11	14	15	2	2	2								50
47.5			2	6	9	18	17	9	2								63
52.5				1	3	13	12	12	4	3							48
57.5				1	1	1	6	9	5	5							28
62.5						1	4	2	2	5	1	1					16
67.5							1			3		1	1				6
72.5												1	1				2
77.5														1			1
82.5										1				1	1	2	5
87.5																1	1
Number of observations	2	7	24	34	31	51	43	34	15	17	1	3	2	2	1	3	270

$r = +0.841 \pm 0.012$, or 84.1.

[2] Garber, R. J., McIlvaine, T. C., and Hoover, M. M. A study of soil heterogeneity in experimental plots. Jour. Agr. Res. (U.S.), Vol. 33, No. 3, p. 259. 1926.

Among the factors that influence farmers in their purchases of fertilizers are returns, price per ton, and effects produced on soils. The problem regarding choice of similar fertilizers like the nitrogen carriers may be resolved into two questions: namely, Which will prove to be the most economical or profitable? and What is the comparative monetary value of one fertilizer as compared with another, based on effectiveness?

Owing to the fact that returns are the most important factors that determine the use of fertilizers, the problem of evaluating them in terms of dollars and cents is discussed, not for the purpose of questioning the value of source-of-phosphorus and source-of-nitrogen experiments, but rather to call attention to certain errors that should be avoided. These errors will be discussed under different "cases."

Case I involves the error of using different bases. This error may be illustrated by the following comparison of phosphates, in which comparative values are based on percentages of net profit:

Average Cost of Phosphate per Acre	Average Net Profit per Acre (Value of Increase Minus Cost of Fertilizer)	Percentage Net Profit (Based on Cost of Fertilizer per Acre)
\$4 for rock phosphate	\$15.00	375 percent
\$8 for superphosphate	\$21.60	270 percent

It would seem that rock phosphate has proved to be the more profitable fertilizer, because it has returned a net profit of 375 percent, as compared with 270 percent from the superphosphate. But the practical fact is, the superphosphate has given an average net return of \$6.60 more per acre than rock phosphate. In agricultural research, this error has many forms.

The following arbitrary data will serve for cases II to VI, inclusive.

Fertilizer A contains 15 percent nitrogen, and sells for \$30 a ton, in good mechanical condition.

Fertilizer B contains 20 percent nitrogen, and sells for \$27 a ton, in good mechanical condition.

Assume transportation and other costs the same, to simplify matters.

Average yield obtained with phosphate and potash fertilizers but without nitrogen is 338 pounds of seed cotton an acre.

"A," applied at an average rate of 180 pounds an acre (27 lb. N), has produced an average yield of 670 pounds of seed cotton an acre, or an average increase of 332 pounds.

"B," applied at an average rate of 136 pounds an acre (27 lb. N), has produced an average yield of 630 pounds of seed cotton to the acre, or an average increase of 292 pounds.

Assume value of seed cotton at 4 cents a pound.

Case II involves the error of ignoring comparative effectiveness of the fertilizers concerned.

Data Used

One pound of nitrogen in fertilizer A costs 10 cents.
One pound of nitrogen in fertilizer B costs 6.75 cents.

Inasmuch as the nitrogen in fertilizer B costs 3.25 cents less per pound than that in fertilizer A, it would seem that fertilizer B would be the cheaper and more economical. But the fact is, the value of the greater increase obtained from fertilizer A more than offsets the difference in cost of its nitrogen.

Case III involves the error of using different acreages in computing comparative values.

Data Used

180 pounds of fertilizer A an acre produced an increase of 332 pounds of seed cotton.

136 pounds of fertilizer B to the acre produced an increase of 292 pounds of seed cotton.

Accordingly, 1 ton of fertilizer A will fertilize 11.11 acres, and would produce a total increase of 3,688.5 pounds of seed cotton; at 4 cents, worth \$147.54 ($2{,}000 \div 180 \times 332 \times 0.04$).

One ton of fertilizer B will fertilize 14.71 acres, and would produce a total increase of 4,295.3 pounds of seed cotton; at 4 cents, worth \$171.81 ($2{,}000 \div 136 \times 292 \times 0.04$).

Inasmuch as fertilizer B, according to this computation, would return \$27.27 more per ton than fertilizer A, it would seem that preference should be given fertilizer B.

Farmers do not buy only a limited quantity of fertilizer, as indicated in the problem, and leave a certain acreage unfertilized. On the contrary, they usually purchase the quantity they need as

based on rate of application and acreage to be fertilized. Moreover, 14.71 acres would return nearly $11 additional profits were they fertilized with A.

When fertilizers are compared on the basis of increases produced, such comparisons should be made on the basis of equal-acreage returns.

Case IV involves the error of computing comparative values of fertilizers on the basis of returns per dollar expended for fertilizer.

Data Used

180 pounds of fertilizer A per acre, costing $2.70, produced an average increase of 332 pounds of seed cotton; at 4 cents, worth $13.28.
136 pounds of fertilizer B per acre, costing $1.84, produced an average increase of 292 pounds of seed cotton; at 4 cents, worth $11.68.
Each dollar expended for A returned $4.92.
Each dollar expended for B returned $6.34.

It would seem that fertilizer B would prove to be the more profitable fertilizer; but the practical fact is, fertilizer A produced a profit of $10.58 an acre above the cost of the fertilizer, whereas fertilizer B produced a profit of $9.84 an acre. Here the error lies in using two different bases ($2.70 and $1.84). Hence the problem is similar to that in case I, where each dollar expended for rock phosphate returned $3.75, and each dollar expended for superphosphate returned $2.70.

NOTE: No suitable data are available for fertilizer experiments in which comparisons are made on the basis of equal expenditure for fertilizers.

Case V involves the error of changing the "company" of basic figures, an error in logic.

Data Used

180 pounds of fertilizer A produced an average yield of 670 pounds of seed cotton to the acre, or an increase of 332 pounds.
136 pounds of fertilizer B produced an average yield of 630 pounds of seed cotton to the acre, or an average increase of 292 pounds.

The relative effectiveness of fertilizer B, as compared with A, is rated as 88 percent. It seems proper to assume that the nitrogen in fertilizer B is 88 percent as effective as that in fertilizer A. Accordingly, it may be assumed that the 400 pounds of nitrogen in 1 ton of fertilizer B is equivalent in effectiveness to 352 pounds of the kind of nitrogen in fertilizer A ($2{,}000 \times 0.20 \times 0.88$).

With fertilizer B at $27 a ton, the nitrogen equivalent in B is worth 7.67 cents a pound. (2,700 ÷ 352).

Inasmuch as there are 300 pounds of nitrogen in 1 ton of fertilizer A, and since each pound of equivalent nitrogen in B costs 7.67 cents, the value of fertilizer A, as compared with B, should not be greater than $23.01 a ton. Thus the selling price of fertilizer A is too high by $6.99 a ton. But the fact is, fertilizer A has returned 74 cents more net profit per acre (above cost of fertilizer) than fertilizer B.

The relative rating of 88 percent for fertilizer B is derived from a relative comparison of increases resulting from equal-nitrogen applications of fertilizers A and B. Thus the proper company of 88 percent is *seed cotton* and not nitrogen. The proper use of 88 percent consists in determining what increase in yield of seed cotton may be expected from an equal-nitrogen application of fertilizer B when average results for fertilizer A are known. For example, if, under average conditions, 180 pounds of fertilizer A produced an average increase of 332 pounds of seed cotton, 136 pounds of fertilizer B per acre should produce 88 percent of 332 pounds, or 292 pounds.

Moreover a comparison like that in case V implies the assumption that 154 pounds of fertilizer B per acre (27 lb. nitrogen equivalent), under general conditions, would give the same average results as 180 pounds of fertilizer A (27 lb. N), which lacks support of any experimental data. The comparison also implies a false comparison of 11.11 acres treated with fertilizer A at the rate of 180 pounds to the acre, with practically 13 acres treated with fertilizer B, at the rate of 154 pounds to the acre.

Case VI. In this case true comparative values are based on returns per acre, and validity of source-of-nitrogen experiments is granted.

Data Used

180 pounds of fertilizer A per acre, costing $2.70, produced an average increase of 332 pounds of seed cotton; at 4 cents, worth $13.28.

136 pounds of fertilizer B per acre, costing $1.84, produced an average increase of 292 pounds of seed cotton; at 4 cents, worth $11.68.

Fertilizer A returned a net profit (above cost of fertilizer) of $10.58 an acre, or 74 cents more an acre than fertilizer B, which is equivalent to 27.4 percent interest on the money expended for fertilizer A.

These questions arise: With fertilizer B at $27 a ton, what is the theoretical comparative value of fertilizer A per ton? and, conversely, With fertilizer A at $30 a ton, what is the theoretical, comparative value of fertilizer B?

Inasmuch as the 74 cents greater net profits in favor of A is based on $30 a ton for A and $27 a ton for B, the comparative value of A per ton would be proportionately greater than $30, as the value of the 180-pound acre application is greater than $2.70 by 74 cents, or as $2.70 is to $3.44. Hence, with fertilizer B at $27, the comparative value of fertilizer A per ton is $38.22 ($30:x::2.70:3.44$).

Conversely, with fertilizer A at $30 a ton, the value of fertilizer B would be proportionately less than $27 as the value of the 136-pound acre application is less than $1.84 by 74 cents, or as $1.84 is to $1.10. Therefore, with A at $30 a ton, fertilizer B would have a comparative value of $16.14 ($27:x::1.84:1.10$).

Summary. For practical purposes, return per acre from equal-nitrogen applications is the logical basis for determining comparative values of similar fertilizers, for four principal reasons: (1) relative rating should be taken into consideration; (2) recommendations regarding rate of application of fertilizers are usually made on the acre basis; (3) generally, farmers base the quantity of fertilizers they need on rate of application and acreage to be fertilized; and (4) farmers are particularly interested in expenditures for fertilizers and in the true returns from such expenditures.

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REVIEW QUESTIONS

1. What are some of the problems involved in the interpretation of fertilizer results? Illustrate.
2. What is the meaning of the term "probable error" in statistical analysis? Give an example.
3. Demonstrate the meaning of probable error by the tossing of three coins.
4. Illustrate "average deviation." How may it be used?
5. Demonstrate the use of "standard error."
6. Given two results expressed as two means that do not differ greatly, how may one determine, mathematically and otherwise, whether there is any significance in their difference?
7. Under what conditions may "probable error" be used? Illustrate.
8. What is the relationship between methods of statistical analysis to the sciences?
9. What is the relation of common or practical sense to statistical methods?
10. In the sciences, what is the meaning of correlation?
11. A plot gave a yield of 5 bushels of wheat the first year, 10 bushels the second, and 5 bushels the third. If the relative trend in yield is expressed as 100 percent gain (+100) followed by a 50 percent decrease (—50), there would be an average annual percentage increase in yield of 16⅔ percent (+100—50÷3). Is this reasonable? Explain.

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